Final Technical Report (FTR)

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Executive Summary:

The U.S. Photovoltaic Manufacturing Consortium (US-PVMC) is an industry-led consortium which was created with the mission to accelerate the research, development, manufacturing, field testing, commercialization, and deployment of next-generation solar photovoltaic technologies. Formed as part of the U.S. Department of Energy's (DOE) SunShot initiative, and headquartered in New York State, PVMC is managed by the State University of New York Polytechnic Institute (SUNY Poly) at the Colleges of Nanoscale Science and Engineering.

PVMC is a hybrid of industry-led consortium and manufacturing development facility, with capabilities for collaborative and proprietary industry engagement. Through its technology development programs, advanced manufacturing development facilities, system demonstrations, and reliability and testing capabilities, PVMC has demonstrated itself to be a recognized proving ground for innovative solar technologies and system designs.

PVMC comprises multiple locations, with the core manufacturing and deployment support activities conducted at the Solar Energy Development Center (SEDC), and the core Si wafering and metrology technologies being headed out of the University of Central Florida. The SEDC provides a pilot line for proof-of-concept prototyping, offering critical opportunities to demonstrate emerging concepts in PV manufacturing, such as evaluations of innovative materials, system components, and PV system designs. The facility, located in Halfmoon NY, encompasses 40,000 square feet of dedicated PV development space. The infrastructure and capabilities housed at PVMC includes PV system level testing at the Prototype Demonstration Facility (PDF), manufacturing scale cell & module fabrication at the Manufacturing Development Facility (MDF), cell and module testing, reliability equipment on its PV pilot line, all integrated with a PV performance database and analytical characterizations for PVMC and its partners test and commercial arrays. Additional development and deployment support are also housed at the SEDC, such as cost modeling and cost model based development activities for PV and thin film modules, components, and system level designs for reduced LCOE through lower installation hardware costs, labor reductions, soft costs and reduced operations and maintenance costs.

The progression of the consortium activities started with infrastructure and capabilities build out focused on CIGS thin film photovoltaics, with a particular focus on flexible cell and module production. As marketplace changes and partners objectives shifted, the consortium shifted heavily towards deployment and market pull activities including Balance of System, cost modeling, and installation cost reduction efforts along with impacts to performance and DER operational costs. The consortium consisted of a wide array of PV supply chain companies from equipment and component suppliers through national developers and installers with a particular focus on commercial scale deployments (typically 25 to 2MW installations). With DOE funding ending after the fifth budget period, the advantages and disadvantages of such a consortium is detailed along with potential avenues for self-sustainability is reviewed.

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Background:

The United States Department of Energy (US DOE) funded the development of advanced solar photovoltaic-related (PV) manufacturing processes through its Sunshot initiative to help the solar power industry overcome technical barriers, reduce costs for PV installations, help the US regain the lead in the global market for solar technologies, and provide support for clean energy jobs for years to come. The United States Photovoltaic Manufacturing Consortium (USPVMC) was built on the consortia experience, program management expertise, and world-class R&D capabilities of the Semiconductor Manufacturing Technology (SEMATECH) to solve common PV manufacturing problems by leveraging resources and sharing risks with industry partners. The industry-led consortium focused on the following goals:

- Perform research and development (R&D) to reduce costs at the cell and module level
- Expand partnerships and create the world's leading PV center
- Provide turnkey access to and utilization of leading-edge infrastructure for programs, processing, prototyping, and analytical capabilities
- Capture worldwide respect through marketing and public relations
- Build an advanced manufacturing development facility to speed development and scale-up of CIGS materials, processes, equipment, facilities, and products (proprietary access to development line and manufacturing scale MDF)
- Provide industry support for testing and reliability, balance of system, technology commercialization, and workforce development
- Develop CIGS roadmap and standards driving technical consensus for the CIGS industry
- Establish CIGS manufacturing development facilities to provide immediate access to small scale CIGS development pilot line and labs
- Establish baseline device fabrication processes and parallel processing capabilities
- Establish SPC, APC, MES and other manufacturing controls and technical support
- Benchmark CIGS industry cost/performance best manufacturing practices
- Develop cost models and manufacturing improvement tech transfer IP
- Establish equipment improvement teams to improve capital expenditure cost/watt
- Establish ESH programs to mitigate materials risk, drive recycling, and conserve resources
- Develop programs focused on materials, cell, equipment and integrated processing that drive cost, efficiency and reliability solutions
- Utilize development lines, MDF and baseline flows for industry to develop all layers of CIGS modules

- Develop off-line and in-line metrology technologies that improve yield and reliability
- Demonstrate process control, efficiency and return on investment from manufacturing yield improvements
- Develop correlations between metrology results and cell/module efficiencies
- Identify CIGS failure modes and mechanisms to develop device models that improve product understanding and reliability
- Develop specialized test cells/structures and accelerated reliability testing methodologies that demonstrate/validate product lifetimes
- Develop and optimize PV power electronics
- Improve integration approaches for CIGS BIPV
- Develop innovative module architecture and embedded systems
- Establish PV commercialization support structure to provide incubation and start-up support
- Initiate workforce development programs beginning in college/university curriculums, USPVMC and member company internships, and in-line manufacturing training

Project Objectives:

As PVMC was a member driven consortium with a wide array of topics the SOPO and associated milestones are numerous and cover a large number of efforts. The following is a list of the major objectives in each budget period followed by the significant accomplishments. While many of the reports were only provided to funding partner members, there is a list of public publications in a following section for additional details. Also note that in order to be consistent with prior reports the SOPO language summaries are written in a "to be performed" future tense, with the accomplishments in a "work completed" past tense phrasing. This is intentionally done due to reviews during the budget period with both the DOE and funding partners that may have changed some of the areas of focus.

Budget Period 1 and Budget Period 2

A Statement of Project Objectives (SOPO) was developed for the first two Budget Periods (Years 1 and 2), and was modified and updated in successive Budget Periods to reflect the changing economic/industrial environment, as well as the Consortium learnings.

A. Project Objectives

The U.S. Photovoltaic Manufacturing Consortium, which includes SEMATECH, The Research Foundation of State University of New York (the Foundation), acting on behalf of the College of Nanoscale Science and Engineering (CNSE), and Photovoltaic Manufacturing Consortium, Inc. (PVMC, Inc.), will enter into a Strategic Alliance Agreement devoted to accelerating the development, commercialization, and manufacturing of next-generation PV technologies.

PVMC, Inc. is a new 501(c)(6) not-for-profit corporation formed by the Research Foundation of State University of New York acting on behalf of CNSE and SEMATECH, Inc. to carry out the objectives of the Department of Energy's Photovoltaic Manufacturing Initiative (PVMI). The Recipients will support the DOE's SunShot initiative by harnessing the interdisciplinary capabilities required to rapidly develop and deploy breakthrough solar technologies, as opposed to making incremental progress. The Recipients will coordinate a multi-faceted industry-driven collaborative R&D initiative to advance CIGS manufacturing process, tools, and materials, and in partnership with the University of Central Florida (UCF), will develop c-Si metrology and wafering technologies. The Recipients will establish a CIGS manufacturing development facility that PV companies and researchers can use for product prototyping, demonstration, and pilot- scale manufacturing to evaluate and validate the CIGS PV manufacturing technologies they develop, which will reduce the cost and risk of commercializing them. In partnership with the PV industry, the Recipients will develop a PV

Technology Roadmap to guide the industry in assessing R&D needs and opportunities for innovation. The Recipients will operate complementary programs to incubate new PV technologies and firms, and to develop the U.S. PV workforce. The financial goal of PVMC, Inc. is for all operations and programs to be self- sustaining with respect to DOE PVMI funds at the end of the five year term. PVMC, Inc. will be headquartered in New York State.

B. Project Scope

The PVMI is intended to accelerate the coordination of stakeholders and fund technology development efforts across the solar industry and, with other state and federal policy incentives, facilitate the development of a strong PV manufacturing industry and supply chain in the U.S. The ultimate goals of this initiative are to support the creation of a robust U.S. PV manufacturing base, develop a highly trained workforce with the critical required skills, and speed the implementation of new cutting edge technologies.

The Recipients will conduct organizational, strategic and technical programs to accomplish the ultimate PVMI goals. Based on industry feedback, Recipients' initial portfolio includes programs in:

1) Roadmaps and Standards,

2) CIGS PV Manufacturing Development Facility,

3) CIGS PV Manufacturing Productivity Programs,

4) CIGS PV Commercialization Support Structure,

5) PV Workforce Training Initiatives,

6) CIGS Process and Equipment Optimization,

7) CIGS Manufacturing Processes and Metrology Development,

8) CIGS Reliability Development,

9) Balance of System Programs for CIGS PV systems, and

10) c-Si Metrology and New Wafering Technologies

C. Tasks to be performed

Overview:

The overall tasks to be performed on this project are defined in this document. The specific tasks set forth below are intended to accomplish the following by the completion of the DOE award. The tasks are to establish the U.S. PV Manufacturing Consortium organization, create and maintain a CIGS roadmap for U.S. industry, create and operate a CIGS manufacturing development facility, execute technical programs that enhance CIGS module capability and manufacturability, establish a commercialization support structure for US CIGS manufacturers and suppliers, and to develop a highly-trained CIGS workforce. In addition, advanced c-Si wafer and measurement R&D will occur. The milestones used to evaluate progress against the tasks defined in this document are contained in the Project Management Plan.

A brief summary of the milestones of BUDGET PERIOD 1 and BP2 are included here:

Statement of Project Objectives Summary for Budget Period 1 & Budget Period 2:

Organizational and Strategic Objectives: Create a single leadership governance structure overseeing the CIGS manufacturing development facility in New York as well as the research programs in Florida comprising a management team of industry leaders and university experts that serve at the Board, technical advisory, and management levels which will provide member-driven direction and oversee selected program agendas, detailed tasks and milestones, and timelines to accelerate commercialization of required materials, tools, processes and products for the CIGS facility and also provide overall guidance for the c-Si research activities. Develop and disseminate Technology Roadmaps and Standards with a 10 year timeframe (updated yearly) and organize national workshops that invite industry, universities, national labs, and DOE industry focused consortiums to build and integrate PV research, technology development, and innovation networks.

Establish advanced CIGS pilot lines for multi user prototype/pilot production that enable proprietary development efforts across the entire value chain; and establish a CIGS Manufacturing Development Facility (MDF) to increase US PV Manufacturing market share, jobs and technology innovation. Enhance manufacturing productivity and yield through cost effective methods for SPC, automatic process control, automatic equipment control, PV optimized MES (Manufacturing Execution System), run-to-run control, fault detection, and e-diagnostics. Create a robust pathway and support structure from innovation to commercialization. Develop hands-on education and training programs to develop the skills needed for Tera-Watt (TW) scale PV manufacturing and deployment in the U.S. through student training, job banks, business training, and PV workforce development programs.

Technical Objectives:

Process Equipment Technology Working Group: Optimize manufacturing processes and equipment to close the efficiency gap between lab production and commercial production of high efficiency CIGS cells; Work with US industry partners to provide access to Best Known Methods (BKMs) processes, test technologies, equipment, correlation testing/modeling capabilities, and programs to optimize manufacturing parameters/components that lead to high efficiency commercial production.

Metrology Technical Working Group: Develop CIGS Manufacturing Processes and Metrology for Next Generation High-Efficiency, High-Volume Production Lines by establishing and operating a platform that facilitates development of in-line, high-speed, non-destructive, test and metrology equipment that monitor key metrics and predict performance

Reliability Technical Working Group: Develop methodology for CIGS reliability enhancement by characterizing CIGS materials and process integration interactions to develop specific models around failure mechanisms, performance, and yield to provide direction for process, equipment, metrology innovations and establish standards that improve yields and profitability.

Balance of System (BOS) Technical Working Group: Develop BOS Technologies that reduce cost and improve the performance, reliability, and functionality of CIGS PV Systems through reduced cost elements, improved mounting, and incorporating "smart module" technologies

c-Si Program: Develop In-Line / Off-Line Metrology Systems that increase line yield and improve manufacturing productivity, and support the introduction of new wafer methodologies that achieve lower-cost, less energy intensive c-Si Substrates by using thinner wafers, methods for reduced energy/Wp, minimizing Si losses, improving wafer grinding, and advancing wire saw operations etc.

Annual Stage Gate Reviews and Project Reporting: The stage gate review will be based on the Project Management Plan, based on the Stage Gate review results DOE will provide direction to: 1) proceed without modification, 2) proceed with modification; 3) hold the program until further information is provided; or 4) stop the program with no further DOE support; Reports and other deliverables will be provided in accordance with report requirements, following the instructions included therein.

Project Results and Discussion:

The USPVMC as a membership-driven consortium established partnerships with companies and organizations throughout the PV industry to collaborate on programs addressing common, pre-competitive infrastructure needs including national laboratories and research partners, cell and module manufacturers, material suppliers, equipment suppliers, and end-users with a goal of carrying out the objectives of DOE's Photovoltaic Manufacturing Initiative. The recipients coordinated a multi-faceted industry-driven collaborative R&D initiative to (1) advance CIGS manufacturing processes, tools, and materials, (2) accelerate the development, commercialization, manufacturing, field testing and deployment of next-generation PV technologies and systems, and (3) in partnership with the University of Central Florida (UCF), develop c-Si metrology and wafering technologies.

NY-PVMC had recruited 60+ Partner companies, with 40+ collaborative agreements signed. In total there were 27 collaborative projects with direct industry participation. Below is the summary of significant accomplishments by Budget Periods (BP 1-6)

BP 1 & BP2: CIGS Roadmap for a 10 year period was created and was made available for the members of the consortium

CIGS Road Map: The CIGS roadmap prepared over a two-year period by individuals from SEMATECH, the College of Nanoscale Science and Engineering, and industry representatives headed by "*The PV Roadmap Leadership Team—Larry Kazmerski, Joe Laia, and Dick Swanson*", resulted in a 10-year map for the different components of the photovoltaic manufacturing chain, including materials and substrates, rigid and flexible, metrology, and reliability requirements

The mission of the U.S. CIGS PV roadmap effort was to help the U.S. PV industry meet the U.S. SunShot Initiative goals of "reducing the total installed cost of solar energy systems by 75%." Road mapping identified the critical challenges for CIGS PV manufacturing and applications and defined the areas of innovation and technical developments needed to advance and sustain a competitive US photovoltaic industry.

The first roadmap workshop was held July 2011. This first meeting was attended by a broad base of the U.S. CIGS industry, with cell and module manufacturers, equipment and materials suppliers, and researchers to explore if there was industry desire for a road mapping effort. Through a series of voting and discussion the attendees decided the most important focus topics: Metrology, Roll-to-roll, Rigid Glass, Substrates and materials, Modules and packaging, Reliability/Certification/Test, thus forming the basis of the first U.S. CIGS PV Roadmap. Teams were formalized: the Roadmap Leadership Team, the broader Roadmap Executive Steering Committee (RESC) and the six working group teams.

The second roadmap workshop was held in 2012, sponsored by the PVMC and hosted by the SEMI PV Group at InterSolar North America. This workshop was followed by a public forum with presentations for initial progress on each of the six roadmap topics

List of Working Groups and challenges identified in each category is listed below:

1) Rigid Glass

Developing standards on glass dimensions, Understanding and controlling Na introduction from the glass, Incoming glass quality, Glass washing/surface preparation, Understanding and improving glass dimensional stability, Glass temper condition, Glass thickness and Manufacturing process improvements

2) Roll to Roll

Number and consistency of quality flexible substrate suppliers, Increased performance of CIGS on flexible substrate to that of glass, Central to closing the performance gap is developing the best method to extrinsically introduce sodium, Lack of standardization of deposition tool roll handling hardware, Uniformity control for large-area CIGS processes, Metrology tools required for R2R manufacturing, Developing low-cost robust cell-to-cell interconnects that provide long term reliability, Equipment standardization (control protocols, interface, data collection and web registration),Temperature uniformity and control over large-area substrates, Substrate barrier coatings, Improved technology to enable longer runs.

3) Modules and packaging

Scale of CIGS commercial manufacturing, Module size optimization per application, Acceleration of CIGS efficiency, Buffer layer replacement, Hermetic at the CIGS cell, Standard module backside configuration for attachment, Low-cost cell interconnection, Low-cost flexible substrate for roll-to-roll processing, Packaging material quality effects on reliability, System model optimization, Lower-cost top sheet structures for flexible and Low-cost alternatives for incorporation of bypass diodes

4) Substrates and materials

Substrate smoothness and cleanliness, Thinner absorber, Limited understanding impact sodium, Limited insight in purity requirements, High cost of Ag interconnect materials, Lower-cost, higher-performance TCO, Cd-free buffer, Higher bandgap, Recycling, Lower cost substrates

5) Metrology

Predictive correlation between absorber-only metrology and final performance, Multipoint, rapid depth dependent composition, band gap, and crystallographic orientation measurement on large area substrates, Low-cost temperature measurement of moving or stationary components with changing emissivity, Reliable circuit measurement without special circuit configurations ,Large area (full size) macro level defect spatial mapping, Ex situ nanoscale chemical and electrical metrology that directly correlates measurement to performance, Post junction formation probing/scanning for voltage mapping and performance prediction, Generating a library of meaningful device performance characteristics that enable translation of high efficiency lab scale processes to manufacturing and to commercialization of CIGS thin film PV products, Multiscale simulation and modeling of system, panel, device, and material based on first principles for correlating data from multiple metrology methods and informed decision making, Standards in metrology for accelerated lifetime testing and failure analysis

6) Reliability/certification/ test

Better correlation between accelerated reliability testing and field performance is needed, International Electrotechnical Commission (IEC) testing standards are not sufficient to guarantee 25-year field performance, Lack of data sharing of reliability and failure data, Mechanisms that cause failure modes are not well understood, Large standard deviation on derating light soak stability/FF degradation, IEC testing protocols not always correlated with quality control (QC) processes, In situ manufacturing metrology data not widely used for predicting failure modes/degradation rates

Summary of Final technical recommendations: Current CIGS process technology has been demonstrated to achieve slightly above 20% conversion efficiency at standard test conditions

(STC) for very small cell sizes, thus demonstrating that the capability but not necessarily the fundamental understanding exists. Commercially relevant, cell efficiencies that range from 15% to 17% have been reported and verified for a number of CIGS absorber deposition process technologies. These cells have yielded commercial size CIGS solar panels with module efficiencies that range from 13% to 16%. This begins to compare favorably in terms of efficiency relative to current polycrystalline silicon photovoltaic based solar panels of 14% to 15% but is low relative to current single crystalline silicon based solar panels at 21% efficiency.

Significant improvements in basic CIGS understanding, coupled with improved manufacturing process control and finally advancements in CIGS photovoltaic cell architecture will be necessary to establish this technology as a major contributor and commercial significance.

Substrate capability improvements in support of metal substrates is required in terms of common specifications based on fundamental understanding of the relationship between surface chemistry, surface topography, barrier technology, and reactive chemistry minimization at current and future manufacturing process temperatures and times. A substrate capability improvement in support of polymer substrates is required in terms of higher manufacturing process temperatures and duration times.

CIGS manufacturing improvements that will benefit both at the CIGS web yield level as well as simplifying the module design requirements include several aspects. Near-term improvements in TCO layer properties in terms of hermeticity, transparency, and conductivity could be leveraged by the CIGS industry within current manufacturing environments. Developments in shunt management (minimize creation and development of a post passivation process) coupled with improvements in the reduction in susceptibility of the creation of regions of low reverse voltage beak down is needed.

The CIGS heterojunction requires a system-level focus as an alternate, more environmentally benign buffer layer is selected and a manufacturing process is developed and optimized in conjunction with the introduction of dopants capable of achieving an increase in the operational band gap. Increases in absorber deposition throughput, a currently slow process rate, can be successfully achieved by the industry by combining a reduction in overall absorber thickness with an efficient back reflector technology. Additional advantages in lower CIGS processing time at maximum temperatures would reduce web barrier requirements and enable additional classes of polymers as candidates for polymer web selection.

Early stage work developing an additional junction, a move from single junction to optimized multi-junction should be continued and aligned for introduction as single junction CIGS photovoltaic cell architectures achieve conversion efficiencies of the mid 20% to enable the continuation towards a goal of 30% conversion efficiency.

Opportunities for supporting research include the following:

Substrate web specs, Higher temperature polymer substrate, Advanced TCO development, Shunt passivation and the like, Alternate buffer layers, High band gap (dopants), Reduction in absorber thickness, Development of back reflector technology, Move from single junction to multi-junction

The challenge for roll-to-roll manufacturing is to meet the very premise that attracted the CIGS community, that is:

- Promise of high production volumes in low cost, low foot-print systems.
- Low cost defined in terms of $/W CAPEX and $/W OpEx.
- Ability to separate processes into completely independently control systems (i.e., very large batches) that allow each unit process to be independently optimized.
- Enabling unique market sectors such as BIPV, but with robust and reliable cell-to-cell interconnects.
- Process and control uniform films at high web speeds, with roll widths greater than 1 meter wide and roll lengths that are several thousand meters long.

While there are several organizations pursuing R2R, arguably none have been able to commercialize on the benefits of R2R manufacturing. The inability for R2R to become the dominate CIGS technique can be generally broken down into two major categories: 1) equipment operation issues, true yield, equipment standardization, and incoming substrate quality, and 2) lower overall efficiency for CIGS deposited on glass in comparison to CIGS deposited on metal or polymer foils. These two major categories conveniently fit well within a 5-year goal and a 10-year goals described below.

5 Year Goal:

Substrate quality and consistency—Number one as a critical challenge is quality of incoming substrate. While less of a concern for polymer derived substrates, both metals and polymers have unique features compared to glass. For polymers, one major challenge is the balance between coefficient of thermal expansion (CTE), coefficient of moisture contraction (CME), and heat shrinkage as well as the anisotropy of these properties associated with web direction (cross or trans). Substrate consistency changes from run-to-run and depending on storage conditions.

Metals on the other hand suffer most from rolling induced defects in the form of contaminates for "roll lines." Currently, there is a void in data that directly correlates substrate induced defects with yield or performance. Needed is data that correlates web quality to performance. That information can be used to develop data derived specifications. Specifications can be used to enable substrate suppliers to develop the infrastructure to meet the needs for R2R CIGS.

Web speed and control—For CIGS R2R manufacturers, web speed is usually the first metric quoted with comparison high speed food packaging. However, typical CIGS web speeds are 10 to 100× slower than other R2R industries. Part of the challenge for high speed R2R CIGS is process and part is equipment. Much of the CIGS equipment employs free-span webs and the strategies for web control are different than with high speed polymer coating for industries, such as with food packaging.

Cost minimization—With most of the above areas addressed, the promise of high speed for R2R CIGS manufacturing (metal foil specific) comes to an abrupt stop at cell-to-cell interconnection. Current collection grid printing, cell segmentation, and cell-to-cell interconnection are expensive and slow. These three areas represent almost the same cost of the remainder of the solar module packaging (encapsulants, edge seal, j-box, label frame).

Without a low-cost solution to interconnect, R2R may not ever achieve costs on par with Si. Part of the problem is in the available inks. CIGS cannot withstand the same processing temperature during grid printing and solder interconnection as for silicon. This results in a very poor translation in Ag conductivity (i.e., paying ~10× more for the Ag because the printed ink conductivity is so poor).

10 Year Goal:

The original attractiveness of R2R CIGS included

- The ability to enable unique products using flexible cells and encapsulation,
- The ability to completely separate unit processes into large batches thereby increasing the ability to refine
- and control each layer individually, and
- Ability to process at high web rates.

While the attributes above may enable smaller niche markets, with recent cost reductions in Si technology the above attributes may be insufficient for R2R to capture significant market share of the much larger traditional field installed PV market. To be competitive, CIGS must now be lower in cost and higher in efficiency to compel large installations to consider CIGS. Overcoming the lack of long term field reliability data could become a major hindrance.

Since the solar cell is not the major cost, further reduction in cost of the deposition technologies will not have a major impact on cost. R2R has taken most of the cost out with the exclusion of the commodity materials. What remains to reduce cost is efficiency (or $/m2). Improvement in efficiency in essence amortizes the cost of the grid and encapsulation materials over more watts.

In the laboratory, efficiency of CIGS on foil lags glass substrates by 2-3% absolute. Significant research is needed to close this gap and further close the gap between theoretical efficiency and HVM efficiency. Improvement in efficiency comes from three major areas:

- Understanding the roll of Na and developing robust repeatable approaches for extrinsic introduction into CIGS
- Increased band gap. Increasing band gap to 1.4 to 1.5 eV provides more headroom with regard to the maximum theoretical efficiency. Moreover increasing band gap has two other major benefits:
    - Increasing band gap reduces J_{SC}, thereby decreasing the thickness and increasing the percent transmission of the TCO. Decreased thickness of the TCO will decrease cost and narrow the gap between theoretical efficiency and HVM efficiency.
    - Reduction in J_{SC} also allows fewer printed grid lines or wires. Fewer lines or wires also decreased cost and reduces losses from grid shadowing.
- Improved buffer layers that improve the short wavelength current collection. While inroads are being made with ZnS (ZnS(OH)), wide band gap buffers need further development and refinement.

Success Factors:

The key success factor for R2R CIGS is to achieve conversion efficiencies comparable to c-Si with costs that are roughly competitive. Moreover, the cost will likely need to be less than silicon until long term field performance data is available for CIGS. R2R provides the potential for low cost but the low cost cannot be at the expense of performance. Also key to the success of CIGS is time. The solar industry is changing quickly and the current growth may pass by pre-competitive technologies. The next five years are crucial for R2R CIGS in determining the commercial viability and bankability.

Critical factors in reducing cost and increasing performance are interrelated. Included are:

- High quality consistent substrate
- Standardization of incoming substrate quality and consistency. Cost and efficiency impact of substrate material includes:
- Increasing total factory yield and increasing efficiency by eliminating substrate induced defects.
- Increasing substrate lengths reduces down time from roll changes but increases importance of roll handling and handling related defects.
- Eliminating the need for diodes integrated into the module.
- Efficiency competitive with crystalline silicon
- Improved efficiency represents one of the primary approaches to decrease installed cost per Watt. The majority of complete solar module costs has been reduced to commodity materials, in particular final encapsulation materials. Increased efficiency amortizes the cost of the materials over a greater number of Watts. Central focus for increased efficiency are extrinsic Na addition, increased band gap, and wide band gap low loss window and buffer layers.
- High speed, large area processing
- The industry recognizes the value in increasing manufacturing scale both in terms of line speed and substrate width and continues to push forward with technology innovations in material handling and large area deposition sources. Both of these factors will be critical in driving down the cost of capital equipment costs per annual capacity in Watts. ($/w CAPEX.)

Thus the PVMC CIGS Roadmap provided a detailed overview of the current status of CIGS industry and the necessary factors to be considered for improvement. As per consortium guidelines, the reports were available for consortium members alone, therefore the CIGS Roadmap was not shared with other entities even though there was interests from different international entities.

Significant technical accomplishments during BP1 and BP2:

During BP1 and BP2, apart from the road map activities, the Technical Working Group (TWG) meetings were held to get inputs from Consortium members. Based on the voting during the first two years of the project, the focus was mostly in equipment and supplies to set up the infrastructure required to build out our service capability. During this period, a strong network was organized that included thin-film PV manufacturers, equipment suppliers (manufacturing and metrology) and consumable vendors (high purity targets, metals,chemicals, etc.).

During the first two years US-PVMC established partnerships with companies and organizations throughout the PV industry to collaborate on programs addressing common, pre-competitive infrastructure needs including national laboratories and research partners, cell and module manufacturers, material suppliers, equipment suppliers, and end-users.

In Budget Periods (BP) 1 and 2 three Technical Working Groups (TWGs) were formed: Process and Equipment, Metrology and Reliability. Each TWG managed several projects simultaneously along with extensive work on:

1. The development of the "Manufacturing Development Facility" (MDF), consisting of a facility to deposit large area thin film photovoltaic stacks (back contact, absorber layer, buffer layer and transparent front contact) , by sputtering and evaporation on stainless steel web in roll-to-roll configuration
2. The development of a "Back end of the line" (BEOL) facility and processes for module fabrication.

1. Development of Manufacturing Development Facility" (MDF):

In CIGS MDF line, baseline multistage CIGS co-evaporation processes were established using PVMC CIGS Process control system and repeatability was established for 1sigma < 0.8% . The NREL splits measured 1sigma <0.3%. Thus PVMC demonstrated that it can emulate and enhance co-evaporation process which is used in many of our partner's production line.

2. Equipment development for factory scale up

Partners evaluated equipment technology readiness for expansion of production capacity which included qualifying supporting materials & hardware development

- Worked in conjunction with US equipment and solar materials / module manufacturers

- Effort reduced risk and shortened lead time required to qualify module architecture builds

-Developed and installed a state-of-the-art 1m CIGS evaporation source integration prototype with a commercial partner, leveraging a one-of-a-kind 1m thin film processing capability developed at PVMC

COST Model:

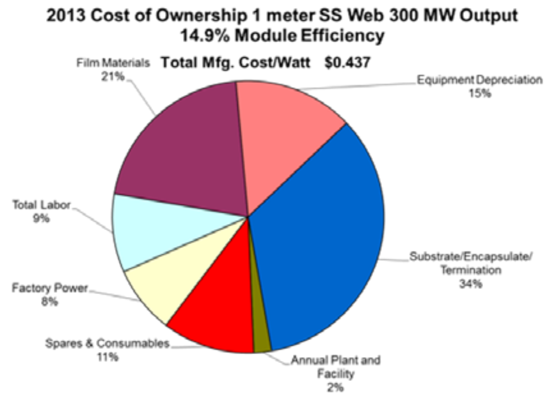
Developed Cost of ownership model for CIGS Roll-to-Roll 300MW output plant; A synopsis of the cost model is shown below:

Mods to "Upgraded MDF Style"

- 300MW Capacity
- Cell performance from 15 to 16.2%
- Sub + Mod to 0.15$/W
- 20% lower equipment capex (0.6$/W)
- Uptime increased from 70 to 85%

Notable Unchanged Assumptions

- 1meter wide web, 2.5km length
- Yield at 90%
- Glass front and back sheet
- Wire grid with 92% packing density
- 7 /25 Year depreciation schedules



Base Substrate Material		SS Web
Encapsulation Method		Glass
Substrate Material Leading Edge	m	1.00
Substrate Material Trailing Edge	m	2500.0
Substrate Edge Exclusion	cm	1.0
Aperature Efficiency	%	16.2%
Yield	%	90%
Estimated MW Factory Output	MW	300.0
Modules Yielded / Year	#	3,038,772
Required Cell Area/Year	m^2	2,236,536

Module Characteristics	
Module Width(m)	0.600
Module Length(m)	1.200
Active Area %	92%
Include Frame?	No
Active Area	0.662
Watts/module(w)	98.7
Module Efficiency	14.90400%

Factory Ecomomic Inputs		
Equip Depreciation Period	yrs	7
Burdened Operator Cost / Year	$	45,000
Factory Working Hours per Day	hrs	24
Factory Working Days per Year	days	360
Cost/M2 of Building per year	$\$m^2$	$150
Buliding/Plant Depreciation Perio	yrs	25
Power Cost KWH	$/kwh	0.10
Fab Space Required	m^2	8,946
Office/Warehouse (35% of Fab)	m^2	3,131
Annual Building Cost	$	$1,811,594
Annual Water Costs $/($km^2$)	$	$100

Select Programmatic achievements by the TWG's

- Process & Equipment Program
  - Demonstrated alternative buffer layer (Cd-free, ZnOS) by sputtering
  - Developed cost model to show ~10% reduction in manufacturing cost for alternative process
- Metrology Program
  - Developed prototypes for CIGS reference cells
- Reliability Program
  - Developed SOW for evaluating rigid CIGS panels for their durability under various standard and advanced test conditions.
- Cross-cutting Program
  - Published first CIGS industry roadmap
  - Completed cost models for rigid and roll-to-roll CIGS module manufacturing processes

C-Si Program at UCF:

Smaller efforts were established on c-Si metrology and new wafering methodologies, conducted by the University of Central Florida.

The crystalline silicon (c-Si) activities of the U.S. Photovoltaic Manufacturing Consortium (PVMC), headquartered in New York, went through a Pareto exercise in 2012 with 38 separate organizations from PV industry, national labs and academia to identify and prioritize the critical challenges in c-Si feedstock/wafering. These challenges are organized into four different production areas: feedstock production; ingot/brick production; wafer production; and cross-cut, i.e., multiple production areas. Identifying the most significant c-Si feedstock/wafering hurdles is the first step in initializing collaborative R&D consortium projects that will spur U.S. industry progress in c-Si feedstock and wafering solutions.

Primary goals of initial program areas of c-Si technology are listed below:

1. In-line/Off-line Metrology

– Identify critical industry needs in metrology and rank

– Develop projects to demonstrate new c-Si metrology technologies

– Transition new metrology technologies into pilot and manufacturing lines

Current 5-Yr Program Area Goal (revision expected by WG)

– >1,100 wf/hr in-line tool, reducing yield loss such that cost of insertion is offset completely

2. New Feedstock/Wafering Methodologies

– Identify necessary feedstock/wafering targets for $/W

– Establish cSi feedstock/wafering programs to accelerate transition of new technologies into mainstream manufacturing

– Provide and foster process, test, and demonstration activities to validate new technologies and identify technical barriers

Current 5-Yr Program Area Goal (revision expected by WG)

– Demonstrate silicon usage efficiency < 3g/W and c-Si wafer cost reduction of >50% to below $0.25/W.

<u>BP3 - Statement of Project Objectives Summary:</u>

3.0 Organizational and Governance activities: Continue program and project review process with Executive Board and Executive Technical Advisory Board (ETAB) and secure and recruit members and expand financial contributions and submit quarterly reports and review meetings. Establish and Manage c-Si PVMC consortium, programs, and associated collaborative projects

4.0 LPV Project: LPV Project was designed to help the CIGS module manufacturers to reduce the BOS costs and to accelerate the adoption and market penetration of LPV in commercial installation market. It had five distinct sub projects with a systematical approach of understanding the LPV market, existing mounting mechanisms, its economic and reliability impact. Based on the survey, new LPV mounting mechanisms which will reduce cost of installation need to be identified and implemented by demonstrating the improved installation method and recording actual cost for installation of a real world 2kW system using a commercial installer.

Lightweight PV (LPV) Market Analysis: Characterize LPV market based on the most viable U.S. states for rooftop, determine LPV potential (sq. ft.) in commercial and industrial (C&I) segments in top 5 states and determine serviceable available market (SAM) for specific building and roof type make report web-accessible to members. The contributing partners were GSE, MiaSole, Johns Manville, Tecta, Solar Frontier

LPV Mounting Mechanisms: Survey current LPV mounting mechanisms and processes and evaluate durability of attachment mechanisms (interface between module and roofing material, e.g. adhesive, lamination, and mechanical clamps) via accelerated testing. Develop innovative mounting mechanisms to attach lightweight PV modules to roofing materials. Survey existing standards for LPV; define and promote standards for accelerated testing of mounted LPV systems. Contributing Partners were GSE, MiaSole, Johns Manville, Tecta, Solar Frontier

LPV Prototype Demonstrations: Benchmark cost of installation of LPV systems by comparing the commercial rooftop installation cost model with NREL and RMI models. Establish LPV BOS cost model and methodology by installing 2kW baseline systems using commercial installation contactor and record costs. Use LPV installation cost model and data collected using installation measurement protocol to analyze at least one LPV installation and recommend cost reduction opportunities. Evaluate outdoor performance of mounting mechanisms and compare them with indoor testing, and monitor outdoor system performance data. Utilize alternative mounting mechanisms, and install using revised installation measurement protocol and operate systems while documenting any differences in performance, cost or failures in the alternate mounting mechanisms. Compare outdoor failure modes with those identified in accelerated tests in Mounting Mechanisms project. Contributing partners were GSE, MiaSole, Johns Manville, Tecta, Solar Frontier.

LPV Module Integration: Quantify reduction in BOS costs for LPV installations through a targeted "Integrated Module" architecture that includes incorporating a sacrificial membrane into existing industry module fabrication processes by defining categories for BOS costs relating to the Integrated Module attributes. Get PVMC partner consensus on Integrated Module attributes for generating additional cost projections and identify Pareto of cost reduction opportunities. Utilize cost information, prototype Integrated Module development and test site installation(s) for validation, thereby demonstrating the potential to achieve a LPV BOS reduction equal to 30% of hardware labor costs for installations at the MW scale.

Once cost reduction is established, design and prototype Integrated Module (with sacrificial membrane) and processes for LPV applications and develop proof-of-concept for fabrication and submit LPV Integrated Module specification sheet with projected reduced BOS and impacts to Integrated Module fabrication costs. Build integrated module with pre-packaged modules, cells or strings and materials supplied by industry integrated with sacrificial membrane backer sheet and review installation of large area laminator leading to a Go/No-Go decision for automation equipment required for layup, diode attach, and edge seal.

Based on "go" approval from partners, complete large-area lamination process qualification. Fabricate LPV Prototype Integrated Modules using existing pilot-line scale equipment with materials and cells, strings, or packaged existing modules supplied by industry and perform baseline Integrated Module testing and characterization following IEC / UL style metrics according to the plan approved by contributing partners. Also validate reduced LPV installation / BOS costs by completing installation of the equivalent of 2 kW of integrated modules at a test site and report BOS costs for fabricated LPV in comparison to original projection.
Contributing partners for the LPV project were GSE, MiaSole, Johns Manville, Tecta, Solar Frontier, and Monolith (installer)

5.0 Outdoor Field Performance

The objectives of the outdoor field performance project was to establish outdoor performance testing of new and existing products and serve as the CIGS industry point of contact for multi-regional testing. Apply existing predictive performance models and correlate results from field, indoor accelerated testing, and manufacturer process & design variables. Establish standard O&M practices for CIGS PV Systems and validate the performance of customer sites and commercial arrays installed at CNSE.

The tasks were to survey industry partners for specific measurement needs and protocols for creating four CIGS 5 kW arrays, and a larger 200 kW CIGS array by designing outdoor arrays and to finalize the design and installation plan by determining the number of modules per string, inverters, mounting methods for flex and rigid modules, use of trackers. Create list of specifications for the 5 kW installations that include required hardware, system design, Data Acquisition System & metrology equipment needs and identify component suppliers and installer/contractor for the larger 200 kW system, select installation methods and finalize the design and installation plan for this system. Establish a test plan that includes baseline measurements, protocols for continuous monitoring including environmental variables and identify inspection approaches for reporting and analyzing failures. Once installation design is approved by partners, obtain baseline data, install 5KW and 200 kW arrays

Complete preliminary report on performance, detailing all available data, such as array power output, weather data, O&M events, warranty failures, identified failure modes, etc. Finalize Scope of Work and agreements with Regional Test Centers to serve as the CIGS industry point of contact for multi-regional testing as requested by participants.
Validate CIGS Customer arrays, establish agreements/commitments on participating customers sites and establish details of plans for data collection, analysis and dissemination, obtain historic data from the site and create preliminary assessment report with explanations comparing with models, including assumptions, data and vetting, BKM for field monitoring of CIGS and O&M methods and provide monthly analysis and reports for aggregate and proprietary data.
Contributing partners for outdoor performance project were Global Solar, MiaSole, Tecta, *Solar Frontier*

6.0 Performance Measurements Standards

Maximum power determination of a thin film CIGS modules is a challenge on account of the various measurement practices used in the light soaking methods by different CIGS companies. Performance measurements standards project objectives were to develop measurement standards and protocols for Thin film CIGS that allow accurate prediction of actual field performance based on Light soak stabilized maximum power determination, Temperature coefficient determination, and Power output determination under low irradiance conditions. The results thus obtained will be compared against the manufacturers "name-plate measurements" and decide if PVMC and partners will initiate modification of IEC 61646 to make use of these findings. Also develop a solar simulator with extended spectral range in the infrared, to better reflect the spectral response of CIGS photovoltaics and with software for temperature coefficient determination.

The tasks were to a) determine appropriate light soak stabilization method for maximum power determination, b) to determine temperature coefficient measurement protocol, and c) determine a protocol for measurement of power output under low irradiance conditions for both CIGS and c-Si modules and analyze and report results of different partners' modules and difference between cells and modules from same partner and to determine candidate protocol(s) for comparison with outdoor testing results.

To obtain outdoor performance data for CIGS and c-Si modules, install modules outdoors at the Halfmoon facility (two modules per manufacturer), or at the CNSE roof. Monitor, analyze, and report performance for a minimum of three months. Create protocols that improve predictions between indoor tests and outdoor performance and publish the results with partner's approval and make decision regarding activities to change protocols in IEC 61646

Contributing partners: GSE, MiaSole, SolarFrontier, Spire, Newport

7.0 Metrology for Manufacturing

Establish the capability of spectral reflectometry or polarimetry as a thickness and composition monitoring metrology technique applicable to the majority of CIGS module layers and deposition technologies and demonstrate feasibility of process control analytics while building a database relating growth conditions and layer properties.
Install Optical Monitoring Terminal (OMT) in sputtering line at PVMC pilot line and calibrate system based on off-line characterization. Collect data and evaluate metrology techniques to decide between reflectometry and polarimetry for CIGS deposition. Benchmark in-line measurements with off-line characterization and ellipsometry-based optical models. Go/NoGo decision to be made between regular fiber optics and polarization maintaining fiber optics at this point. Based on the decision, analyze the deployment of full-demo system at a manufacturing facility. Contributing partners: Accustrata, University of Toledo

8.0 Indoor Accelerated Lifetime Tests (IALT)

Objectives of the IALT project were to design and establish advanced indoor testing plan to replicate near- and long-term failures to identify failure modes by a) isolating stress conditions-IEC type and b) using combinatorial stress conditions-IEC type in a dark environment c) using stress conditions which are directly related to observed outdoor conditions by using combinatorial stress factors (Temperature, Relative Humidity, light and load). Compare and classify failure modes from tests in dark and light, identify root cause of failure and establish the correct set of advanced indoor ALT protocols to replicate observed failures using combinatorial stress factors observed outdoors.

The tasks of IALT project were to design indoor ALTs for identifying failure modes by isolating stress conditions in dark and light-illuminated environment, and generate report on individual and combinatorial tests including sample size and measurement methodologies and characterizations (temperature, IV, EL and IR), required to meet project criteria. The projects samples were to be obtained from industry module manufacturers with baseline performance specifications (min of 5 modules for each of the 6 tests - 30 modules in total) and have control module for each of the individual tests.
Coordinate and initiate individual and combinatorial stress ALTs to perform dry heat tests at 4 different temperatures, Damp heat (DH) and Temperature Cycling (TC) and Humidity Freeze (HF) for extended periods of time periodically until the performance is characterized by a failure >15% P_{max} while retrieving modules every 200h for intermediate characterization (IV, EL and IR) using the proper light soaking protocols.

In a similar way, coordinate solar thermal humidity cycle tests where the test modules are exposed under light while it is subjected to DH, TC and HF and compare the results with the IEC type tests and classify failure modes based on results from all the tests above. Submit a report on establishing the correct set of indoor ALT protocols to replicate failures using combinatorial stress factors.

Contributing partners: GSE, Stion, Atlas and Intertek

The following projects and tasks correspond to the c-Si part of the program, run at UCF.

M-P2: Optical and Electronic Characterization of Wafers and Passivation Layers

Objectives were to provide member companies with access to samples with consisting of varied wafers, emitter types and passivation layers and a)to correlate material properties and c-Si/dielectric interface characteristics to passivation performance using QSSPC along with advanced materials characterization methods (e.g. HR- TEM EELS) for aluminum oxide (AlO_x) passivation (APCVD, ALD) b) Evaluate various recombination characterization methods as a means of tracking the evolution of minority carrier lifetime through the various cell manufacturing process steps and c) to demonstrate feasibility of extracting spatially-resolved recombination and electronic/electrical information (e.g. net dopant concentration, Rs, Rsh) about wafers and cells using PL (for wafers) and EL (for cells).

M-P4: Metrology Needs for Emerging c-Si Technologies

Objectives were to Identify new metrology-related challenges associated with emerging c-Si technologies (e.g. n- type wafers, thin wafers, Ag-free metallization, new passivation materials) and to prioritize challenges based on industry feedback and member company preferences and to evaluate, improve upon and (where necessary) develop the necessary metrology methods to overcome challenges in these areas.

FSW-P1: Diamond wire (DW) sawing of mono-crystalline silicon ingots

Objectives of this project were to benchmark of commercially available diamond wires (120µm diameter) from at least four different suppliers; understand failure modes associated with diamond wire sawing and correlate to developed test methods; improve the longevity of the diamond wire in order to reduce the cost; Evaluate the feasibility of using RUV technique for quality control and/or real-time monitoring of diamond wire for level of wear; Establish correlation between the ingot properties (stress, impurities, shape) and as-cut wafer properties (TTV, stress, etc.) and to establish correlation between diamond wire properties and as-cut wafer properties (mechanical, optical, electronics).

FSW-P7: Crack Formation and Location as a Function of Incoming Wafer Properties

Objective of this project were to establish correlation between the initial stress distribution, thickness and its variation, of incoming wafers to crack length/location, failure strength; establish correlation between the bow/warp of incoming wafers to crack length/location, failure strength; establish the stress budgets (thermal or applied) for various handling and process steps.

Project Results and Discussion:

BP3 & Pivot of PVMC Focus Areas:

By the end of BP 2, many of the US photovoltaic manufacturers were closing their doors, so with input from both DOE and the surviving member companies, the PVMC focus moved towards other links in the PV chain, such as installation and performance. The structure and target of the projects pivoted for BP3, with emphasis in Light-Weight Photovoltaics (LPV). The consortium membership also reflects this change, with the addition of roofing companies, PV installers and developers, the consortium efforts switched from "Manufacturing" to a broader view of the solar market. An example of both broader scope and consortium nature was the consensus on the need for better performance measurement standards that allowed a direct comparison between the different photovoltaic technologies, in particular to be able to compare the performance of c-Si modules with that of thin film ones in a meaningful manner. In unanimous agreement, the manufacturing member companies requested the development of measurement protocols to determine maximum power output and temperature coefficients. Another effort related to the new emphasis on LPV was carried out on the back end of the line, establishing connections between PV manufacturers and roofers to improve PV back sheets and ways to install them.

The "Process and Equipment" TWG gave way to "Lightweight PV (LPV) Market Analysis", "Mounting Mechanisms", "Prototype Demonstrations", "Balance of Systems" and "Outdoor Performance" groups. The metrology and reliability TWGs included projects dealing with testing protocols, standards development, and field performance. The "Prototype Deployment Facility" (PDF) was built to facilitate projects related to Mounting Mechanisms and Prototype Demonstration, and efforts were initiated to install arrays at Regional Test Centers (RTCs).

Additionally, there were proprietary projects (fully paid for by the interested parties) such as (but not limited to):

- Development of processes for one of the CIGS manufacturers using the MDF
- Testing of a novel optical metrology system in the MDF by partner
- Assistance to one other CIGS manufacturer by part of PVMC's technical personnel, who traveled to their facility to jumpstart production

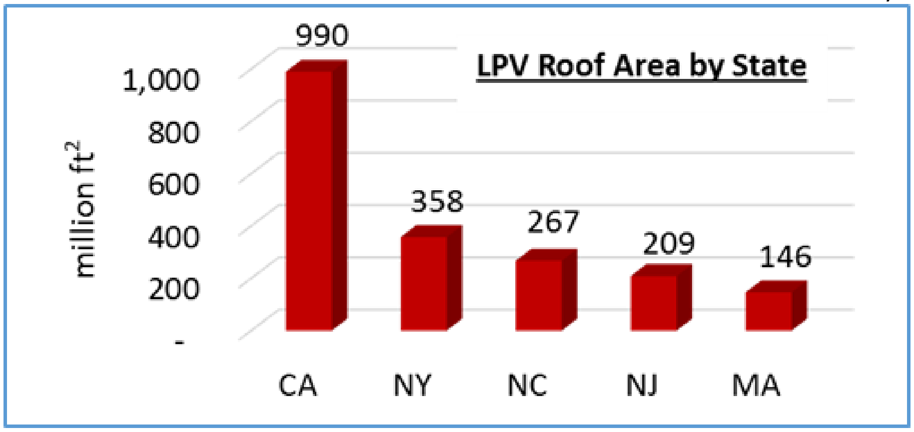
- Finishing of photovoltaic stack (deposition of buffer layer, transparent oxide contacts, and contact grids on company provided CIGS) for partner, and subsequent sample characterization (I-V, XRF, etc.)
- Analysis of alternative, lighter, flexible substrates for CIGS-based light weight PV for partner

Lightweight PV – LPV Market Analysis: The LPV Market Analysis was done in collaboration with ECG consulting group, focused on enabling PVMC partners to drive down customer acquisition costs by identifying attractive markets for their products and to mitigate risk of new product development and deployment.

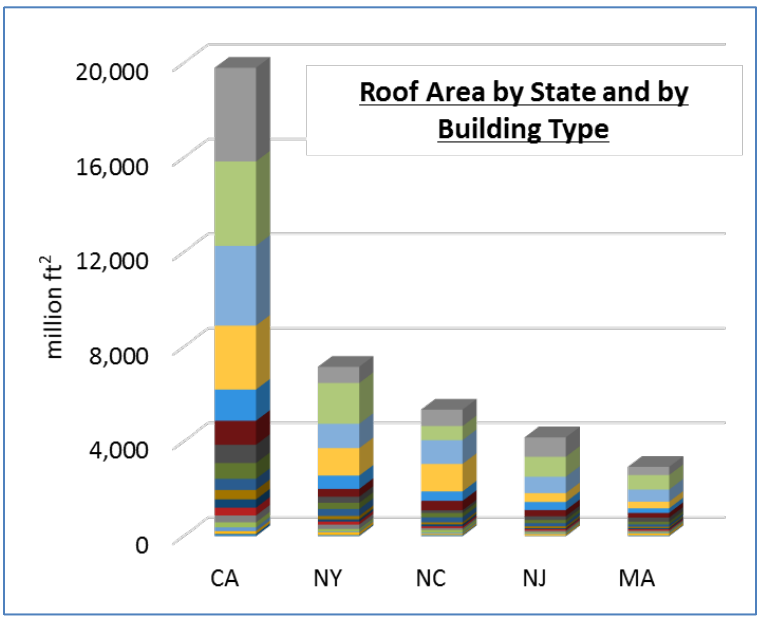
This market analysis report was used by all our CIGS manufacturers, and it is important to be mentioned that there were many requests from other CIGS non-member companies too.

Key Takeaways of the LPV Market Analysis:

a. LPV appears to be an enabling technology that can drive improved solar system performance and functionality for rooftop installations; for example, lighter weight may mean lower material, shipping, transportation and installation costs, as well as faster installation
b. Key drivers of LPV penetration and growth are the ability of the technology to meet or exceed the performance and cost of conventional technologies
c. Potential market for rooftop LPV is very large in the 5 states (CA,NY,NC,MA,NJ) analyzed
    i. Area of rooftop for LPV exceeds 1.97 billion ft^2
    ii. Potential capacity 9.85 GW worth over $24.6 billion
    iii. 5 states account for ~30% of U.S. GDP
d. LPV warehousing, manufacturing and retail industry segments represent the most attractive market segments; interviewees stated that modern warehouses and big box retail stores may be building types more likely to value LPV
e. Pre-engineered and wood frame building types appear to be the most attractive frame type market segments of the non-residential building market because these buildings tend to be built closer to the building standards and codes
f. California is the largest potential market for LPV in the U.S.;
New York appears to the next most attractive geographic market



- Completed a market analysis for commercial and industrial (C&I) PV to characterize corporate acquisition strategies, standardization opportunities, and technical barriers to implementation
- Prioritized the top five states for rooftop lightweight PV (LPV) and calculated market potential: 10.2 million buildings, 1.97 billion ft^2 and 19.7 GW



PVMC identified the C&I market to be very large, but technical barriers are preventing realization of its full potential

LPV penetration into the market: (Mounting mechanisms for LPV)

To reduce the technical barriers which prevent the realization of the full potential of LPV penetration and to expedite the LPV penetration into the market, where c-Si panels would not be a structural and economical fit, specific steps were taken to address the gaps in the niche market particularly for the Light weight PV.

PVMC conducted a survey of over 200 PV & roofing standards to determine the standards & codes mounting technologies will need to adhere to for commercial deployment and found 6 standards directly pertaining to mounting technologies, and 21 standards found for LPV. Also PVMC evaluated existing and develop innovative mounting mechanisms to attach both rigid and flexible PV modules and to study the durability of the entire LPV system ((PV module, attachment, roofing material) via accelerated testing, and screened for material cost.

PVMC's **prototype demonstration facility (PDF)** validates outdoor performance & cost of mounting systems. It allowed

- One of a kind facility dedicated to rack-less, ballast free PV installations
- Unique LPV mounting concepts such as sacrificial layer, ENRGYCurb, etc. tested prior to commercial deployment
- Benchmark cost of installation of LPV systems by deploying systems in the field
- Determine the effect of mounting mechanisms on outdoor performance of modules
- Compare outdoor failures with indoor testing failures

Integrated Module packaging was developed to

- Quantify reduction in BOS costs for LPV installations through a targeted "Integrated Module" architecture that includes incorporating a sacrificial membrane into existing industry module fabrication processes.
- Utilize cost information, prototype Integrated Module development and test site installation(s) for validation, thereby demonstrating the potential to achieve a **LPV BOS reduction equal to 30% of hardware labor costs** for installations at the MW scale.

Integrated Module packaging demonstration– "Triple" module using 3 Flex modules

- Enables tri-fold for transportation and module movement on roof
- Form Factor: 3.3m x 1.82m (folded to 1.1m X 1.82m for shipping; 3.7ft X 6ft)
- Performed "Mock Installation" to get placement and alignment times for the CAT
- A team of 2 hardware laborers can transport, place and align ~280kW per day




Cost analysis tool (BOS-CAT) was developed with inputs from actual accounting data provided by PVMC partner. For a 1MW Flexible install in the Northeast region, with a direct attach using Unisolar 144W module and excluding module price, profit, financing; the hardware labor for LPV accounts for ~18% of BOS

Using the Cost Analysis Tool (BOS-CAT) it has been demonstrated that one could reduce hardware labor cost by 71%, excluding indirect costs by creating an integrated module packaging at the factory.

Integrated module packaging allowed for

- Simultaneous lamination of flexible module and sacrificial TPO membrane resulting in overall cost saving.
- Innovative module design and mock installation projects a BOS reduction of >30% hardware labor using PVMC's Cost Analysis Tool
- TPO sacrificial membrane lamination process window to overlap with current flexible CIGS module lamination processes.

Metrology: Measurement standards and Metrology for Manufacturing

Measurement standards project developed measurement protocols for CIGS cells and modules that allow more accurate prediction of actual field performance based on:

- Light soak stabilized maximum power determination
- Temperature coefficient determination

– Power output determination under low irradiance conditions

– Compare with protocols and rating predictions of c-Si modules

Received light soaking protocols from consortium CIGS panel manufacturers and measured temperature coefficients of CIGS panels from 8 different manufacturers including CdTe and c-Si panels. Sample set included 17 rigid and flexible modules.

- Temperature variations dominate the performance of CIGS panels under stable illumination. These variations are more important than previous light soaking history of the panel.
- Heating and cooling rates affect the determination of temperature coefficients on thin film-based panels
- Crystalline silicon panels temperature coefficient are independent of previous light soaking history and temperature rate

Temperature Coefficient(%/°C)				
TC (%/C)	Flex CIGS 1	Flex CIGS 2	c-Si	Rigid CIGS
α (FT)	-0.002	-0.002	0.047	0.012
α (Out)	0.129	0.095	0.006	0.082
α (NP)	0.03	-0.03	0.04	0.01
γ	-0.347	-0.363	-0.412	-0.234
γ	-0.370	-0.355	-0.521	-0.207
γ	-0.43	-0.40	-0.44	-0.31
β	-0.276	-0.244	-0.297	-0.228
β	-0.273	-0.344	-0.374	-0.247
β	-0.33	-0.36	-0.30	-0.30

- The temperature coefficient determination protocol should include steps to avoid hysteresis in the performance as temperature is cycled.
- Temperature coefficient of thin film-based panels increases with low irradiance

Inline –Metrology for Manufacturing.

Established a common metrology technique- reflectometry applicable for monitoring the thickness and composition of the majority of layers (in the CIGS Stack) and will be applicable for many of the deposition techniques inline.

Demonstrate feasibility of process control for CIGS-based photovoltaics in collaboration with partners

Reliability:

Reliability programs goals were to

- Establish the right set of indoor ALT protocols to replicate failures using combinatorial stress factors
- Design and establish advanced Indoor testing plan to replicate near and long-term failures
- Identification of failure modes using stress conditions **which are directly related to observed outdoor conditions** (T, RH, Light and Load)
    - Isolate stress factors (T, RH)
    - Using combinatorial stress factors (T & RH, extra T, HF & TC (or) DH with Bias)
    - Replicating stress factors found in outdoor conditions (T &RH& TC and HF with light, under load)
- Identify the root cause responsible for the failure modes
- Identify the right set of indoor ALT protocols to replicate failures using combinatorial stress factors

A sustainable photovoltaic market is possible only if long term reliability is established. Lifetime of PV modules estimated using accelerated tests should be directly correlated with degradation rates from existing installations. A comprehensive indoor accelerated lifetime test program has been developed by PVMC with industry inputs to address the challenges in understanding the reliability of PV modules. The results of existing IEC protocols was directly compared with modified and extended protocols. Testing of two types of CIGS modules, indicate that failure modes are different with the inclusion of either illumination or biased conditions suggesting differences in the underlying mechanisms.

The result from the "Solar Thermal Humidity Freeze" cycle indicates that modules under light and load exhibited 10-20% degradation than the modules tested in dark condition. The testing has determined that the failure modes are different when modules are tested in conditions which replicate accelerating the stress factors seen by the modules deployed in outdoor conditions in comparison with the DH tests of standard IEC protocols in dark conditions. Based on the results, recommendations are made to understand the effect of identification of the appropriate set of protocols for testing to replicate field failures. The observance of different failure modes indicate that current IEC testing protocols are insufficient to fully determine effects on PV modules deployed outdoors.

BP4 - Statement of Project Objectives Summary:

The eight projects in BP3 were consolidated into 3 projects as per DOE's suggestion to keep reasonable number of milestones

0.0 Governance and Business Development

Continue program and project review process with Executive Board and ETAB by holding quarterly Executive Board and ETAB review meetings. Secure, recruit members and expand financial contributions

1.0 Marketing and Economic Analysis (MEA)

The primary objective of this task is to accelerate the adoption of IPV- and LPV- based systems by identifying market pull opportunities and validating long-term economic return. The tasks of the project were to identify technical features required by target customers and perform economic analysis by generating a bill of materials (BOM) for MRD-specified system configuration, and calculating expected installed cost for MRD-specified system configuration. Contributing Partners: GSE, MiaSole, Johns Manville, Tecta, SoloPower Systems, Monolith Solar, Solar Frontier

2.0 PV Products Development and New Product Introduction for LPV Mid-market Scale Rooftops (NPI)

The primary objective of this project is the development and demonstration of IPV and LPV matched module, mount, and wiring configuration solutions for commercial mid-market scale applications with cost analysis validating lower system costs than ballasted system (excluding module).

Tasks were to perform cost analysis for LPV Configurations (Sacrificial Membrane, Mold Flex, Rigid), in comparison with lamination process characterizations, evaluate mechanical attach and racking for IPV / LPV and review reliability protocols and testing requirements. Develop proof of concept install for projected module / mount / configuration (minimum of 2 demo systems down selected from cost analysis report and partner approval). Define customized module and specification matched to mounting method and determine combinatorial testing requirements.

3.0 System Performance and Operation (SPO)

The primary objective of this project is to drive large-scale PV deployment through a PV predictive performance program that utilizes R&D, commercial and utility scale arrays. The plan is to maintain a central database to collect data from PVMC owned PV installations and generate improved PAN file coefficients. Analyze the characterization protocols at the module level, with the final goal of developing an algorithm that will allow a prediction of outdoor performance for given weather conditions and time of day.

Tasks were to collect PV systems performance data from various installations and aggregate in a central database, and initiate outdoor installations at VT-RTC. Establish protocols for measuring individual module parameters (Tc, irradiation dependence, spectrum, etc.) with panel-to panel performance variability, compare to PVMC PDF performance, Initiate data collection from (a) AC only and (b) instrumented data. Compare outdoor data with other PVMC programs. Run data through system design models (e.g. PVsyst, PVWatts, etc.). Build a module-level PV performance predictor algorithm and use small PV arrays (e.g., PDF, CNSE rooftop) to refine the algorithm methodology

The following projects and tasks correspond to the c-Si part of the program, run at UCF.

1.1 Establish and Manage c-Si PVMC Consortium, Programs, and Associated Collaborative Projects

Objectives of the c-Si PVMC consortium were to maintain and grow c-Si PVMC memberships by carrying out visits/WebEx meetings with targeted potential members; Manage collaborative projects and initiate new projects, Plan and hold valuable workshops, 2015 Joint c-Si PVMC workshops at InterSolar and to establish formal collaboration with BNL

FSW-P1: Diamond Wire (DW) Sawing of Mono-Crystalline Silicon Ingots

Objectives of the project are to benchmark of commercially available diamond wires (120µm diameter) from at least four different suppliers, Understand failure modes associated with diamond wire sawing and correlate to developed test methods, Improve the longevity of the diamond wire in order to reduce the cost, Evaluate the feasibility of using RUV technique for quality control and/or real-time monitoring of diamond wire for level of wear, Establish correlation between the ingot properties (stress, impurities, shape) and as- cut wafer properties (TTV, stress, etc.) and to establish correlation between diamond wire properties and as-cut wafer properties (mechanical, optical, electronics using SEM,EDS,FIB, Confocal microscope, Scanning Acoustic Microscopy, Infrared Polariscopy, Resonant Ultrasonic Vibration, Cathodoluminescence, EBSD/Raman, PL, Reflectance). Analyze results and summarize correlation studies/conclusions and complete with final report or project continuation proposal.

Contributors of the project were: Process Relations, Polaritek, Ultrasonic Technologies, Sonoscan, Attolight, Process Research, Silfex, Sinton Instruments, 3T & Associates, Bomas, Agilent, Hinds Instruments, UST, Niabraze, NREL, FSEC and UCF.

FSW-P7: Crack Formation and Location as a Function of Incoming Wafer Properties
Objectives of this project were to establish correlation between the initial stress distributions, thickness (T), the total thickness variation (TTV), bow/warp of incoming wafers to crack length/location, failure strength, using various characterization techniques and to establish the stress budgets (thermal or applied) for various handling and process steps. If project has completed all tasks, write final report, otherwise write project continuation proposal for PAGs/DOE

Contributors: Process Relations, Ultrasonic Technologies, Polaritek, Suniva, Spire, UST, Sonoscan, NREL, UCF.

M-P2: Optical and Electronic Characterization of Wafer and Passivation Layers

Objectives of this project were: to provide member companies with access to samples with consisting of varied wafers, emitter types and passivation layers, to correlate material properties and c-Si/dielectric interface characteristics to passivation performance using QSSPC along with advanced materials characterization methods (e.g. HR- TEM EELS) for aluminum oxide (AlO_x) passivation (APCVD, ALD) and to evaluate various recombination characterization methods as a means of tracking the evolution of minority carrier lifetime through the various cell manufacturing process steps and to demonstrate feasibility of extracting spatially-resolved recombination and electronic/electrical information (e.g. net dopant concentration, Rs, Rsh) about wafers and cells using PL (for wafers) and EL (for cells). If project has completed all tasks, write final report, otherwise write project continuation proposal for PAGs/DOE

Contributors: Suniva, TauScience, Brookhaven National Laboratory, Spire,

M-P4: Metrology Needs for Emerging c-Si Technologies

Objectives of the project were to identify new metrology-related challenges associated with emerging c-Si technologies (e.g. n- type wafers, thin wafers, Ag-free metallization, new passivation materials) and publish results of Pareto analysis on critical challenges for emerging c-Si technologies in peer-reviewed journal, Prioritize challenges based on industry feedback and member company preferences (Conduct investigation of potential characterization methods of PERC cells, Measure EQE and I-V of >200 p-type cells and determine spectral mismatch, assess feasibility of "spectral binning" as a means of increasing module energy yield in series-connected modules) and evaluate, improve upon and (where necessary) develop the necessary metrology methods to overcome challenges in these areas. Create and submit Project Continuation Proposal to the c-Si Metrology PAG and to the DOE for approval

Collaborators: Applied Materials, Tokyo Electron, DuPont, Jabil, Tau Science, Sonoscan, Sinton Instruments, Suniva

FSW-P8: Mechanical Yield as a Function of Wafer Thickness

Objectives of the project were to integrate metrology to characterize strength of incoming wafers in a non- destructive way (RUV, EL/PL), understand yield associated with sawed wafers and to understand overall cost structure of sawing thin wafers

Contributors: Suniva, UCF, Ultrasonic Technologies

FSW-P9: Proof of Concept Solar Cell Fabrication Using Temp Bonding

Objectives of this project was to demonstrate the feasibility of making a thin solar cell using temporarily bonding to a substrate as a mean to handle/process thin wafers. Tasks include developing and finalizing device design, and preparing mask/screens and determining bonding layer integrity/quality and degas as a function of temp, Single side polishing-bonding, and front and back side polishing with pre deposition cleaning, low temp passivation, Intrinsic a-Si, n-type a-Si, and TCO deposition of metal contacts and characterization.
Collaborators: PVMC, Brewer Science, UCF, NREL, AKRION, MV Systems

FSW-P10: Modeling Thermal Mechanical Effect during Solar Cell Fabrication

Objectives of this project is to understand quantitatively the effects of thermal processing steps on wafers and solar cells by defining processes/parameters, inputs/outputs, and selecting appropriate platform (e.g. ABAQUS) (PVMC, UCF, CENTECORP) and building CAD model(s) (CENTECORP) and modeling of relevant physics and to create and validate a computer model and make it available within the consortium
Collaborators: UCF, CENTECORP, SUNIVA

FSW-P11: Dissolution of Oxygen Precipitate-Nuclei for Making High-Efficiency Solar Cells on Thin, Low-Cost, N-type, CZ-Si Substrates

Objectives of this project is to perform calculation to determine time required to dissolve a given precipitate, demonstrate the flash anneal process as a valid method to mitigate lifetime degradation as a result of processing n-type wafers and investigate whether the flash anneal process works for a wide range of oxygen concentration by determining their average O and C concentrations and minority carrier lifetime (NREL) and by completing design of experiment (e.g. Temperature, Time, O concentration) (NREL) to perform flash anneal experiments (NREL)

and characterize the FA wafers for changes in dissolved O, defects, and minority carrier lifetime (NREL)
Collaborators: NREL, SUNIVA, UCF

FSW-P12: Optimize Diamond Size Distribution and Concentration

Objectives of this project were to optimize size distribution of diamond particles and to optimize diamond concentration by completing design of experiment for diamond wire, sawing and characterizing mechanical properties of unused diamond wires, analyzing as-cut wafers, its surface damage and characterizing mechanical properties.

Collaborators: FSEC, UCF, UST, NIABRAZE

FSW-P13: In-Line Tool for Diamond Wire Quality Control using Resonance Vibrations

Objectives of this project were to implement non-contact DW activation and advanced non-contact detection of the acoustic resonance (both algorithm and hardware) and to demonstrate the RV-DW tool in field testing (diamond wire production or diamond wire sawing) by implementing non-contact DW activation and detection using acoustic resonance and performing Factory acceptance test and create Bill of Materials (BOM), generate technical 2D/3D drawings, and prepare manuals and perform field test.

Collaborators: PVMC, UST, NIABRAZE, PROCESS RESEARCH

FSW-P14: Texturing of Diamond Wire Sawed Wafers

Objectives of this project were to integrate metrology to characterize strength of incoming wafers in a non-destructive way, to understand overall cost structure and yield associated with sawing thin wafers. Tasks will be accomplished by doing baseline measurements: Determining local surface morphologies, determining damage depth of as-cut wafers, Determining pyramid size and reflectance variations, examining variations in the texture size) and improving uniformity independent of damage, and finally by fabricating and comparing solar cells performances.
Collaborators: NREL, PVMC, SUNIVA

FSW-P15: Silicon Wafering – Full-Scale versus R&D-Scale Diamond Wire Saw

Objectives of this project were to produce silicon wafers with a full scale diamond wire saw, using wire from several different sources, perform metrology on wafers and compare with wafers produced on R&D scale saw and to derive trends such as consumables costs (e.g., meters of diamond wire per wafer cut)
Collaborators: Asahi, St. Gobain, DMT/Meyer Burger, NIABRAZE, UCF, FSEC, UST

FSW-P16: Nitride Films Stress Characterization

Objectives of this project were to demonstrate how the interfacial thin film optical properties and stresses relate to the physical parameters of the nitride films (film deposition parameters, thickness, and composition); and to demonstrate how the physical parameters of the nitride films impact the electrical performance of finished photovoltaic cells

Collaborators: Polaritek, UCF, SUNIVA, FSEC

M-P10: Integrated Cell and Module Manufacturing Metrology

Objectives of the project were to identify and prioritize potential metrology insertion points and data management strategies for critical c-Si cell architecture and process flows, quantify cell-to-module losses and create a validated model that can predict module performance in a specific environment from individual cell data (e.g., I-V, QE) and evaluate the value and potential benefits of using quantum efficiency (QE) measurements as criteria in cell binning processes
Tasks were to identify and prioritize potential metrology insertion points and data management strategies for critical c-Si cell architectures and process flows, Characterize and bin cells, fabricate modules and characterize performance and develop module performance model and validate model predictions from experimental data
Collaborators: Tau Science, SPIRE

M-P11: Carrier Recombination Measurement for Different c-Si Cell Architectures

Objectives were to establish relationships between the injection-level dependent carrier lifetime and cell efficiency to enable predictive metrology, assess the accuracy and speed of different cell parameter mapping methods using bias- PL, differentiate recombination current contributions from contacted and non-contacted regions on wafer surfaces and understand the impact on V_{OC} , and determine the extent to which aluminum oxide (AlO_X) field effect passivation can handle high temperatures and exposure to damp heat

Tasks were to perform carrier lifetime measurements, photoconductance (PC), photoluminescence (PL), at three critical points in pPERC and nPERT cell manufacturing: (1) as-cut wafers; (2) front/rear passivated; and (3) finished cells (Sinton Instruments) and establish relationships between the injection-level dependent carrier lifetime and cell efficiency to enable predictive metrology. Perform interface analysis (e.g., C-V measurements) of passivation films and materials characterization of wafers as needed to provide added information to this study). Perform cell parameter mapping by assessing the accuracy and speed of different cell parameter mapping methods using bias- photoluminescence (PL) and perform spectrally-resolved bias-laser beam induced current (bias-LBIC) measurements to measure local I-V curves and to benchmark the bias-PL parameter maps of cell efficiency, I_{SC}, V_{OC}, FF, and RS and investigate methods of mapping implied V_{OC} for non-metallized, passivated samples
Identify possible methods of measuring recombination at metal/Si interfaces with different dopants, doping profiles, and metal contacts; and perform PC, PL, dark/light I-V, Suns-V_{OC}, bias-

LBIC, and other measurements on specially prepared samples to differentiate recombination currents from contacted and on-contacted regions on wafer surfaces. Also perform device simulations to provide further insight into the measurement results; investigate the thermal stability and damp heat durability of aluminum oxide (AlO_x) field effect passivation by measuring carrier lifetime (via PC) and the properties of the oxide/Si interface (via C-V) before and after exposures to various high-temperature steps (>500°C) and damp heat aging and measure critical changes in the passivation properties using materials characterization methods (e.g., FTIR, HR-TEM)

Collaborators: (Suniva, Spire, Tau Science, Sinton Instruments, Brookhaven National Laboratory)

M-P12: Defect Detection and Classification during Cell and Module Manufacturing

Objectives were to develop method of detecting and classifying Kirkendall voids that form at local back contacts in pPERC cells, identify feasibility of detecting voids in module packaging using methods like SAM, Develop methodology using imaging techniques to identify and distinguish various types of shunts (e.g. process-induced, material-induced) and assess the ability to detect shunts and identify their root cause through imaging techniques as a potential process control or quality management strategy for cell manufacturing

Collaborators: Sonoscan, Tau Science

M-P14: Metrology Implementation Protocol for Enhancing Module Reliability Detection

Objectives of this project were to develop a team to embrace this metrology challenge to improve PV module reliability, select the most critical failure mode(s) of interest to the team, determine the origin point of the failure mode(s), develop metrology insertion point(s) to detect the characteristic(s) that lead to the failure, confirm the metrology technique correlates to the failure mode(s) observed and document the project findings
Collaborators: FSEC/UCF

M-P16: Advanced Surface Preparation and Cleaning for c-Si Cell Manufacturing

Objectives of the project were to determine impact different cleaning procedures have on surface recombination velocity on different passivation materials (undiffused samples), to understand the relationships between the surface cleaning techniques and both the passivation material and dopant type and concentration (diffused samples) and combine findings for single report
Collaborators: Akrion, Suniva, Sinton Instruments

Statement of Project Objectives for BP5

NY Technical Tasks Overview:

The overall objective of the collaborative program is to accelerate the adoption of photovoltaics in the US non-residential mid-market (commercial, industrial, and community solar). This objective will be completed through a series of linked projects. PVMC Inc. will collaborate with its partners to assist with the development and deployment of products and services. In particular, PVMC and its partners will work together in the following project areas:

1. Marketing and Economic Analysis: Photovoltaics for Grid Regulated Interconnection and Deployment (PV-GRID)
    a) Collaboration with utilities for identifying barriers to interconnections and opportunities for mutually beneficial PV deployment
    b) Evaluate methods to reduce interconnection costs and shorten approval timelines

2. New Product Introduction for Commercial & Industrial Photovoltaics (NPI- CIPV)
    a) Prototype testing via PVMC's Prototype Development Facility (PDF)
    b) Validation of product specifications and performance via mid- & large-scale testing and system integration targeting system cost reductions of 45% through performance enhancements, installation cost, and O&M benefits, etc.

3. System Performance and Operation for Return on Investment (SPO –ROI)
    a) Comparison of predictive performance models to empirical datasets, with a target of a 25% reduction in the currently modeled % error vs. empirical value.
    b) Reducing O&M cost and improving effectiveness using data analytics, lab and field testing, and PVMC and industry experience to lower yearly cost by 15%.
    c) Evaluation of establishing a central O&M center.

It is important to note that for example, for every 5% reduction in installation cost there is a multiplier effect leading to significant savings for project developers. For instance, one of our partners had an installed capacity of ~51MW in 2014. At $2/W this 5% cost reduction would equate to cost savings of ~5 million dollars for this one developer.

Task 0: Governance and Business Development

Overview:
Maintain a single leadership governance structure overseeing the collaborative projects, including the manufacturing development facility in New York and the research programs in Florida. Comprise a management team of industry leaders and university experts that serve on the Board, technical advisory, and management levels. The Board will include an assigned manager from DOE with non-voting rights. It will provide member-driven direction and oversee selected program agendas, detailed tasks and milestones, and timelines to accelerate commercialization of required materials, tools, processes and products for the CIGS facility and also provide overall guidance for the c-Si research activities.

Secure and recruit members and expand financial contributions. New partner companies join the consortium based upon strategic and industry impact consideration including input from existing PVMC partners. Develop scope of work to reflect budget period objectives. Extend partnership agreements with existing members and expand financial contributions. Establish a sustainability plan beyond existing DOE contract. PVMC will complete the Technology to Market business plan template to outline its strategy for operating after the existing contract with DOE expires.

UCF Governance and Business Development Subtasks
Manage c-Si PVMC collaborative projects and propose/initiate new projects, Maintain/grow c-Si PVMC membership with strong member contribution, Carry out visits/WebEx meetings and hold valuable workshops with targeted potential members, Obtain quarterly cost share certifications from member companies

Task 1: Marketing and Economic Analysis (MEA)

Overview:
This task will involve establishing a formal collaboration between the solar industry (e.g., developers, installers, component manufacturers) and utilities to identify and address barriers to fast and inexpensive interconnection.
PVMC will facilitate discussions with and between developers and utilities (defined here as both transmission operators, independent system operators, and utility representatives such as PUC's and private entities such as EPRI) at both small internal workshops and large conference forums. Suggestions and ideas from both sides, as well as external work in the area, will be combined to produce a list of potential mechanisms to reduce interconnection processing time and overall cost, including those related to customer acquisition. Follow-on work is expected to address these mechanisms and result in mutually beneficial improvements to the interconnection process.
The work in this area is expected to present methods to reduce interconnection costs in the C&I market by 25%, allowing for increased deployment in areas such as LPV, a large potential growth market for CIGS-based PV.
The primary objective of this task is to accelerate the adoption of C&I scale PV by identifying market barriers related to utility interactions.

Subtasks:

1.1.1: Establish the scope of the utility survey and specific target utilities
Milestone 1.1.1: PVMC partners will define a finite list of utilities or representation of utilities for PVMC staff and subcontractors to survey and interview. PVMC will present a list of utilities operating in states that have been previously identified as attractive for distributed PV (see 2014 PVMC report 1.1.1, "Identifying and prioritizing the most attractive U.S. States for Rooftop PV"). The pertinent criteria for evaluating the relevance of particular utilities to PVMC projects are to be determined.

Partners will then assess the selections by ranking with a FOM according to the fit to the market they serve, and PVMC will rank the level of engagement of the selection based on the level of interest in the study and history of working with external entities.
Metric Justification: We need to establish the scope of the utility survey. Since PVMC is seeking detailed information regarding the interconnection process, it suspects that the survey population will be limited a few select utilities. Therefore, PVMC must poll its partners to document the critical characteristics of an ideal utility for survey and identify the target utilities.

1.1.2: Establish method for surveying utilities
Milestone 1.1.2: After selecting the target utilities, PVMC will generate a structured method for surveying and interviewing by engaging outside consulting agencies, partner companies, and industry representatives. The envisioned 1-page interview guide will include a list of questions for various staff groups at utilities, designed to solicit information pertaining to interconnection processing and cost. The specific questions will be reviewed by PVMC partners to ensure that PVMC staff and subcontractors are asking appropriate questions to generate significantly valuable insight. The guide will require a figure of merit score of at least 7/10 before interviews can begin. "Value to Partners", "Value to Industry", and "PVMC Sustainability Fit" will be ranked from 0-10. Value to partners and industry will be ranked by partners, and PVMC Sustainability Fit will be ranked by PVMC.
Metric Justification: In order to increase the likelihood of a valuable survey campaign, a formalized method must first be established.

Task 2: New Product Introduction (NPI)

Overview:
The focus of this task is on evaluating new and existing system components, designs, and installation methods capable of improving system value (lowering installation costs, increasing electrical performance, etc.). Evaluation methods include cost modeling, component level testing (performance, reliability, durability, etc.), and time-and-motion studies for small (<5kW) and mid (5-50kW)-large (>50kW) scale installations. The arrays will also serve as a source of performance and O&M data for subsequent project tasks.
The PVMC Prototype Development Facility (PDF), in conjunction with environmental chambers and other module test equipment at the Solar Energy Development Center (SEDC), will be used for testing and validation at small scale. For large-scale testing, the most effective method and location for testing will be determined. Potential locations include PVMC demonstration sites, DOE Regional Test Centers (RTCs), and partner R&D installation sites.
It is expected that the tested products will be benchmarked versus existing Si-based modules or standard installation components as deemed valuable.
The primary objectives of this task are cost analysis, development, and demonstration of components for C&I installations.
PVMC will also support proprietary manufacturing project for CIGS companies, including SoloPower Systems, Global Solar Energy, Ceres Technologies, and others as deemed

appropriate and with required approvals. The milestones for these projects will be described and agreed to by both parties in proprietary SOWs and the budgets will be approved by the DOE where federal funding will be used.

Subtasks:

2.1.1: Component and configuration research, review, and classification
Milestone 2.1.1: Analytical hierarchy processes will be used to systematically identify which components and configurations are applicable to the C&I market space, and economically and technically valuable to industry, partners, and PVMC. The evaluation matrix will be based on PVMC knowledge, one-on-one discussions with partners and other industry players, and technology-suppliers product specifications. Categories will include, but will not be limited to; installation and long term cost, long term performance, and O&M cost and performance impacts.
FOM will be calculated for each technology evaluated in the AHP. The AHP value will be normalized to 10 to be used in the assessment. The FOM will provide a high weight to the AHP evaluation, but also include other items that are important to identify when selecting projects. This will down-select technologies that not only have strong potential to achieve the 45% cost reduction goal, but also fit within the abilities, timelines, and sustainability plans of PVMC. The 6/10 pass criteria are meant to provide a lower threshold vs. the final selection in 2.1.2, allowing for additional analysis to technologies where details are needed for proper assessment.

Metric Justification: Many technologies could be considered for the NPI evaluation projects. Objective criteria are important to efficient down selection, and this scorecard process provides that initial level of evaluation so that focus is placed on the C&I market. Partner suggestions will be paramount in this process to ensure that the evaluation methodology and technologies under evaluation have potential value to future commercial projects.

2.1.2: Ranking of cost reduction/performance improvement proposals
Milestone 2.1.2: The analytical hierarchy processes will be used to create a rank-order list of the components and configurations selected in the previous milestone that show the greatest potential cost reductions or performance increases. The level of improvement produced by the technologies must be perceived as very valuable to the consortium partners based on the FOM ranking. An expected percentage of improvement will be decided by the Consortium. Categories will be updated as needed to include all pertinent items, but follow the same method used in 2.1.1. Projected cost benefits ranked to identify items which when combined will meet or exceed the 45% cost reduction target.
FOM will be calculated for each technology evaluated in the AHP. The AHP value will be normalized to 10 to be used in the assessment. The FOM will again provide a high weight to the AHP evaluation, but also a high weighting on the value to partners. This is necessary, as the technology development and evaluation hinges on partner financial support, knowledge, feedback, and interactions. The overall impact to industry will also be

considered. FOM will also prioritize PVMC time, budget, and growth & revenue multiplier needs.

Metric Justification: Down-selected technologies must be thoroughly researched before resources are put in place for evaluation projects. This scorecard process and FOM assessment tool provide that detailed level of prioritization and technology filtering. Partner suggestions will be paramount in this process to ensure that the evaluation methodology and technologies under evaluation have a large value to future commercial projects.

Task 3: System Performance and Operation (SPO)

Overview:

The purpose of this task is to develop methods and analytics to maximize the return on PV projects over their functional lifetime.

There are two areas of focus.

1) Predictive Performance Methods and Sensoring for Performance Evaluation
   - Improved sensoring technologies
   - Extent of extensive sensoring
   - Module nameplate vs. actual performance
   - Weather related forecasting
   - Projections on number of field failures
   - Reevaluating long-term performance forecasting based on empirical results

2) Operations and Maintenance: System Designs, Trigger Points, and Procedures
   - Design for O&M
   - Frequency of O&M
   - Trigger points

As many of these items are universal between PV technologies, sample sizes and needs will be developed, and all available and relevant data will be pulled from available technologies & installation types. Differences in measurement needs and value, maintenance requirements, and long-term performance will then be documented as they are observed. The primary objective of this task is the collection and analysis of data from commercially operated arrays to improve predictive performance models and reduce operation and maintenance costs. Improvement in predictive accuracy is targeted at 25%, and O&M cost reductions/operational improvement is targeted at 15%.

Subtasks:

3.1.1: Review of current and future methods of performance predictions for C&I PV

Milestone 3.1.1: Analytical hierarchy processes will be used to systematically identify areas of focus. The evaluation matrix will be based on literature review, PVMC knowledge, and one-on-one discussions with partners and other industry players. Categories will include, but are not limited to; impact on initial project performance projections, impact on long-term forecasting, the level of improvement expected, size and scope needed to test the significance of change.

FOM will be calculated for each area evaluated in the AHP. The AHP value will be normalized to 10 to be used in the assessment. The FOM will provide a high weight to the AHP evaluation, but also include other items which are important to identify when selecting projects. This will down select technologies which not only have strong potential to achieve the 25% error reduction but also fit the abilities and timelines of PVMC. The 6/10 pass criteria is meant to provide a lower threshold vs. the final selection in 3.1.2, allowing for additional analysis to areas where details are needed for proper assessment. Metric Justification: There are multiple areas which could be used to improve predictive performance. These include items such as improved sensoring or more extensive sensoring for accurate comparison to model results, improvements in weather-related forecasting, improved projections on the extent of field failures, etc. Partner suggestions will be paramount in this process to ensure that the evaluation methodology and technologies under evaluation have potential value to future commercial projects.

3.1.2: Detailed selection process
Milestone 3.1.2: After a more detailed review of the areas of focus, the analytical hierarchy processes will be used to systematically identify which areas show the greatest potential for improvements in prediction accuracy. Areas must be perceived as very valuable to the consortium partners based on the FOM ranking. Categories will be updated as needed to include all pertinent items. Projected error reduction benefits will be ranked to choose items which when combined will meet or exceed the 25% target. FOM will be calculated for each area evaluated in the AHP. The AHP value will be normalized to 10 to be used in the assessment. The FOM will again provide a high weight to the AHP evaluation, but also a high weighting on the value to partners. As the support for predictive performance evaluation & improvement hinges on partner financial support, knowledge, feedback, and interactions. The overall impact to the industry will also be considered, as well as the fit for PVMC to act as the development partner and evaluator within the time and budget constraints.
Metric Justification: Areas of focus must be thoroughly researched before resources are put in place for an evaluation project. This scorecard process and FOM assessment tool provide that detailed level of prioritization and filtering. Partner suggestions will be paramount in this process to ensure that the evaluation methodology and technologies under evaluation have potential large value to future commercial projects.

3.2.1: Review of current and future methods of O&M system design, trigger points, and procedures for C&I PV
Milestone 3.2.1: Analytical hierarchy processes will be used to systematically identify project areas. The evaluation matrix will be based on literature review, PVMC knowledge, technology supplier specifications, and one-on-one discussions with partners and other industry players. Categories may include, but are not limited to, implications for system costs, implications for maintenance costs, impact on operational efficiency, impact on system performance, and potential size and scope needed to test the significance of change. FOM will be calculated for each area evaluated in the AHP. The AHP value will be normalized to 10 to be used in the assessment. The FOM will provide a high weight to the

AHP evaluation, but also include other items which are important to identify when selecting projects. This will down select technologies which not only have strong potential to achieve the target 15% O&M cost reduction, but also fit the abilities and timelines of PVMC. The 6/10 pass criteria is meant to provide a lower threshold vs. the final selection in 3.1.2, allowing for additional analysis to areas where details are needed for proper assessment.

Metric Justification: Improvements to O&M have an impact over the lifetime of a PV system. This is perceived to be a high impact area to costs based on discussions with partners, other PV industry participants, and investors. Project areas need to be ranked to determine highest value areas of focus.

3.2.2: Detailed selection process

Milestone 3.2.2: After a more detailed review of the projects, the analytical hierarchy processes will be used to systematically identify which areas show the greatest potential for improvements in O&M efficiency and cost reductions. Projects must be perceived as very valuable to the consortium partners based on the FOM ranking. Categories will be updated as needed to include all pertinent items. Projects which pass the selection criteria will be developed into actionable projects. Projected cost reduction areas will be ranked to choose items which when combined will meet or exceed the 15% target. FOM will be calculated for each area evaluated in the AHP. The AHP value will be normalized to 10 to be used in the assessment. The FOM will again provide a high weight to the AHP evaluation, but also a high weighting on the value to partners. As the support for O&M projects, procedures, and areas of cost reduction evaluation & improvement hinges on partner financial support, knowledge, feedback, and interactions. The overall impact to the industry will also be considered, as well as the fit for PVMC to act as the development partner and evaluator within the time and budget constraints.

Metric Justification: Projects must be thoroughly researched before resources are put in place for an evaluation project. This scorecard process and FOM assessment tool provide that detailed level of prioritization and filtering. Partner suggestions will be paramount in this process to ensure that the evaluation methodology and technologies under evaluation have potential large value to future commercial projects.

Task 4: PVMC Wind Down Report

Subtasks:

4.1.1: Wind Down Report

Milestone 4.1.1: After a detailed review of the project as a whole, the Team will summarize progress toward achieving financial self-sustainability, to include progress against revenue targets, Project management, and plans for the future. This report will highlight the project successes, as well as items that did not pan out as expected.

Metric Justification: To create a visionary overview from experiences taken away from the project.

The following projects and tasks correspond to the c-Si part of the program, run at UCF.

Tasks:
5.1: Agreement between semi-automated contact resistivity measurements and manual measurements
Milestone 5.1: Demonstrate good agreement between semi-automated contact resistivity measurements and manual measurements using a micro-manipulator – all for non-destructive test structures. For this milestone, the mean of ρ_c for each technique from at least 10 cells will be compared.
Metric Justification: Non-destructive ρ_c measurements have been performed on various semiconductor devices using micro-manipulators and electrical source-meter units. However, this approach is manually intensive and cannot be inserted in-line during manufacturing. Even off-line, this is a slow measurement process that can slow development cycles. A semi-automated technique that is forward compatible for insertion as in-line metrology is highly valuable, and agreement with manual, micro-manipulator based measurement will increase confidence in this technique.

6.1: J_0 and/or R_S increase at two irradiance conditions (0.2 kW/m^2 and 1 kW/m^2) for a defective and a non-defective module
Milestone 6.1: Demonstrate the ability to accurately quantify the impact of at least two module defects on the recombination and/or resistive losses of a module. Depending on the defect type selected, parameters like J_0 and R_S will be extracted using the multi-irradiance I-V data and compared to that of I-V curves collected at standard test conditions (STC) only. This work will be assessed using a one-diode equivalent circuit model of a module to illustrate exactly how the multi-irradiance I-V is more accurate in predicting these parameters under field conditions.
Metric Justification: In the field, PV modules seldom (if ever) operate at STC. Normally, modules experience an irradiance lower than 1 kW/m^2, spectrum different than AM1.5G, and temperatures other than 25°C. The performance of modules therefore normally operates below nameplate, and this deviation can be even further exacerbated for modules with defects. Defect identification before module shipment or even for modules in the field is important, but equally important is the ability to quantify the impact of that defect under field conditions. This gives more certainty in the kWh production of that module and provides more confidence in that investment.

6.2: Prototype demonstration
Milestone 6.2: Demonstrate a prototype capable of monitoring module I-V characteristics in situ without needing to manually disconnect the module from the grid-connected inverter or μ-inverter. A report will be created featuring design plans and images of the hardware in operation.
Metric Justification: Current module I-V curve tracers on the market are either not grid-connected, meaning the modules connected to them do not generate in useful energy, or the modules must be manually disconnected from a grid-connected inverter/μ-inverter,

the I-V curve tracer connected, and then the measurement performed. The ability to automatically collect the I-V curve of a grid-connected modules will be demonstrated here.

7.1: Correlation studies completed
Milestone 7.1: We will perform few designs of experiment to investigate how surface properties and wire doubling vary with sawing conditions. We will perform ANOVA analyses to establish correlations.
Metric Justification: Surface properties of as-cut wafers exhibits striations (or pilgrim waves) in a seemingly random way. Three types of pilgrim waves were recently identified; however, it is unclear how each pilgrim waver type relates to sawing parameters, diamond wire properties, and coolant properties. Type 2 pilgrim waves result in smaller surface damage and anticipated increased performance. Being able to control the type of wave produced through sawing parameters for a given diamond wire is desirable. Furthermore, wire doubling is also an issue with diamond wire sawing, an issue that becomes increasingly difficult as the wafer thickness is reduced. Preventing wire doubling results in higher wafer yields.

8.1: Normalized RMS error between reconstructed and actual stress within ingot (e_s)
Milestone 8.1: We will demonstrate that the normalized RMS error between the reconstructed and actual measured stress within ingot (es) is less than 10%
Metric Justification: Residual stress in silicon CZ ingot can lead to cracks in wafers cut from that ingot. In addition, CZ ingots may at times contain crystallographic defects such as slips, twins, etc. All of these can results in PV modules to perform poorly or even to fail. The ability to measure high levels of stress or crystallographic defects before sawing an ingot would help reduce cost and improve reliability.

8.2: Correlation studies completed
Milestone 8.2: We will perform a few designs of experiment to investigate crack creation and growth in encapsulated cells for various module designs. We will perform ANOVA analyses to establish correlations between cracks and finite element analysis, wafer/cell measurements, and module degradation.
Metric Justification: The LoadSpot tool is a prototype and is anticipated to be able to predict future module performance in the field based on data collected on encapsulated solar cell properties subjected to a load. Correlations studies will allow for the validation of the above claim.

Project Results and Discussion:

BP4-BP5:

Adaptations to the Industry changes:

- PVMC made a strategic pivot in 2012 in response to industry involvement in manufacturing R&D
- The burgeoning CIGS industry was slow accept the collaborative model for process-related topics
- However, PVMC learned from its partners that they were interested in collaborating on post-cell manufacturing and commercialization (i.e., market identification and deployment) projects
- PVMC quickly adapted by developing a series of technology development (e.g., BOS component design, prototype testing, performance analysis) and market analysis projects.
- Today, PVMC continues is downstream momentum by engaging project developers, installers, O&M providers, and utilities to maximize deployment channel opportunities for its solar industry partners
- By opting to pursue downstream opportunities, PVMC greatly expanded and diversified its serviceable market, thereby securing business sustainability for the future

Prototype demonstration facility:

- Constructed >25 test arrays for various PV configurations at PVMC's PDF (Prototype Demonstration Facility) and DOE's Regional Test Centers
- Several installers (e.g., Tecta Solar, US Light Energy, Borrego Solar, Prologis, Gehrlicher Solar) began quoting LPV and CIGS projects due to product validation provided by PVMC


CIGS Manufacturer 1


CIGS Manufacturer 2


CIGS Manufacturer 3


CIGS Manufacturer 2 array on Tracker
(Array facing other side)


CIGS Manufacturer 4


VT- RTC Weather station

- Solar Raceway's wire management system graduated from PVMC New Product Introduction program and has since been commercially deployed
- https://sunypoly.edu/news/solar-raceway-and-miasole-announce-commercial-release-unique-solar-raceway-wire-management.html

- PVMC assisted a commercial deployment using the Integrated Module packaging for a CIGS manufacturer in Fairfield CT.
- http://solopower.com/2017/02/deployment-of-new-product-introduction-program-with-commercial-release-of-solopower-systems-integrated-module-packaging/
- https://vimeo.com/194610255/52ef8b608d


PVMC-assisted commercial deployment (Fairfield, CT)

Wire management - Solar Raceway

Systems Operations and Maintenance program

The System Operations and Performance (SPO) group at PVMC is developing predictive performance algorithms for commercially-deployed PV systems. These predictions are used to benchmark the actual production of PV arrays in order to identify maintenance "triggers" and establish maintenance protocols. "Predictive Performance" and "Operations and Maintenance" are the two legs on which the SPO groups stands, a central repository for PV performance data generated by a number of PV installations in a variety of locations. There is tremendous value hidden in these massive data sets, and the algorithms developed by PVMC's Technologists will unlock that value for the benefit of our Program Partners. As a result, the increased confidence in predicting the performance of PV systems and establishing data-driven O & M protocols will lead to improved financing and PV designs, upfront declaration of O & M cost, and increased national deployment.

Predictive Performance

Careful indoor characterization of individual modules, including measurements at various irradiances and cycling temperatures, was used to develop an algorithm to predict output performance. This algorithm was refined by analyzing outdoor performance of similar modules and correlating with weather information with the goal that PV stakeholders can use this algorithm with commercially available PV predictive platforms to reduce the predictive error. The algorithm is in a process of continuous improvement using access to performance data from PV installations of diverse sizes and locations and their respective weather stations. This performance analysis capability is the foundation of PVMC's central repository for distributed energy resources (DERs).

Operations and Maintenance

The core of the Operations and Maintenance program at PVMC is the central repository. Based on the expected output power for the various PV installations (according to the Predictive Performance output) the behavior of the PV correlated to weather conditions is analyzed to differentiate preemptive vs. unscheduled or periodically scheduled maintenance needs. Identification of triggers for maintenance events is a crucial part of the cost control for normal operation of a PV install, as well as avoiding unneeded maintenance responses.

The forward thinking design of the central repository is to lead to two-way communication "control" for improved dispatching of DERs, by forecasting and pairing PV energy production with grid demands.

Significant Accomplishments and Conclusions:

The consortium approach, where the industry as a whole agrees on common problems to leverage resources, comes with pros and cons. In particular, the need for flexibility, even at added financial cost, in order to follow the needs of the industry made it evident, especially when tallying the industry versus bureaucracy time scales.

- Pros

The organization of workshops for partners of the different industrial origins and stages provided grounds for collaborations that otherwise would not have taken place. This was also true for some of the proprietary projects, where users of the MDF (photovoltaic manufacturers) got in touch with some of the equipment suppliers to coordinate designs for new hardware, metrology capabilities and process control monitoring.

The pivot in focus proposed by DOE opened this organization even more, helping connect light-weight PV manufacturers (rigid and flexible) with roofers and installers, designing a package for the products that would reduce installation costs, as well as different mounting mechanisms. As an example, modules manufactured by SoloPower Systems at their Portland, OR, plant, with support from PVMC technical staff, were laminated following the methods developed during one of the "Prototype Demonstrations" projects, and were finally installed at a Fire Station in Fairfield, CT (http://solopower.com/2016/04/solopower-systems-provides-flexible-thin-film-solar-panels-to-connecticut-fire-station/).

Likewise, a consequence of the contacts established as part of the System Performance and Operations projects, EPC companies such as BQ Energy (which specializes on PV installations in brownfields) have teamed up with monitoring companies (AlsoEnergy) and have started running analysis such as infrared thermography using cameras transported by drones (InSky Aerial).

- Cons

The Program Management specified in the Technology Investment Agreement (TIA) signed with DOE requires a strong involvement of the DOE program monitor at each stage of the execution. Ranging from approvals for membership acceptance, project definition, release of purchase orders, and approval of milestones, in theory this management structure insures that the DOE is working side-by-side with the industry in achieving the goals of the SunShot Initiative, under which the PVMC was funded. In practice, the DOE structure moves at a very different pace than PVMC's industrial partners, which resulted in a very inefficient use of resources. For example, in most cases the purchase orders for equipment that was agreed upon when a given project was approved were released between six months and a year after the official beginning of the project. Meanwhile, the milestones deadlines were not modified, which meant that in most cases the projects were carried out without the proper resources required.

Suggestions for the future, or for future consortia

In terms of managing an "industry-led" consortium, it was learned in time that while workshops and presentations were excellent in terms of sharing information and update on state of the art research and development, most manufacturers were reticent to admit to problems, especially process-related issues that were openly discussed one-on-one. In order to obtain feedback and consensus to work on certain projects that would benefit the industry as a whole, a series of anonymous surveys were set up that were very effective in prioritizing issues, preferred solutions and level of interest in the possible projects to attack those issues. The projects were designed based on these survey results and presented to the partners in subsequent workshops, where generally the consensus on approval was high.

- Development of processes for a consortium partner using the MDF
- Testing of a novel optical metrology system in the MDF
- Finishing of photovoltaic stack (deposition of buffer layer, transparent oxide contacts, and contact grids on company provided CIGS) and subsequent sample characterization (I-V, XRF, etc.)
- Analysis of alternative, lighter, flexible substrates for CIGS-based light weight PV
- Regional Test Centers (RTC)- all 5 CIGS companies
- Reliability on modules under real time conditions

The Recipients will maintain CIGS manufacturing development facility that PV companies and researchers can use for product prototyping, demonstration, and pilot-scale manufacturing to evaluate and validate the CIGS PV manufacturing technologies they develop, which will reduce the cost and risk of commercializing them. Similarly, the Recipients will maintain and expand capabilities of the Prototype Demonstration Facility that PV companies and researchers can use for prototyping, demonstration and evaluation of PV system components. The Recipients will operate complementary programs to incubate new PV technologies and firms, and to develop the U.S. PV workforce.

Inventions, Patents, Publications, and Other Results:

There are no inventions or submitted patents under this award

NY-PVMC Projects and dissemination results are summarized.

1. Impacts of Humidity and Temperature on the Performance of Transparent Conducting Indium Tin Oxide and Electrical Interconnects for Solar Applications, Upendra Avachat, Fadong Yan, David Metacarpa and Pradeep Haldar, 39th IEEE PV Specialists Conference, Tampa FL 10.1109/PVSC.2013.6745089
2. Evaluation of reactive sputtering of ZnS in Ar-O_2 environment as a pathway to Zn(O,S) thin-films, Ankush Halbe, Graeme Housser, Michael Gardner, Timothy Groves and Pradeep Haldar, 39th IEEE PV Specialists Conference, Tampa FL 10.1109/PVSC.2013.6744857
3. Evaluation of two-stage $CuInGaSe_2$ evaporation for manufacturing scale up, Daniel Dwyer, Jonathan Mann, Amara Conteh, J. Nicholas Alexander, David Metacarpa, Pradeep Haldar, 39th IEEE PV Specialists Conference, Tampa FL 10.1109/PVSC.2013.6745000
4. Diffusion activation energy of cadmium in thin film $CuInGaSe_2$, N. J. Biderman ; Steven W. Novak ; T. Laursen ; R. J. Matyi ; R. Sundaramoorthy ; Gary Dufresne ; John Wax ; Michael Gardner ;Dave Fobare ; D. Metacarpa ; Pradeep Haldar ; J. R. Lloyd, 39th IEEE PV Specialists Conference, Tampa FL 10.1109/PVSC.2013.6744499 (IEEE-AWARD WINNING PAPER)
5. Selenium flux effects on Cu(In, Ga)Se2 growth rate, and control by in-line X-ray fluorescence, Daniel J. Dwyer ; Sandra B. Schujman ; Jennifer A. Novak ; David J. Metacarpa ; Pradeep Haldar, 39th IEEE PV Specialists Conference, Tampa FL 10.1109/PVSC.2013.6744854
6. Cost analysis and criteria for achieving the SunShot target of$0.5/Wp manufacturing cost using flexible thin film Cu(In,Ga)Se_2 solar cells, David Metacarpa ; Nirav Vora ; Jake Whitbeck ; Adam Garney ; Daniel Dwyer ; Pradeep Haldar, 39th IEEE PV Specialists Conference, Tampa FL 10.1109/PVSC.2013.6744854
7. Evaluation of CIGS cell interconnection methods Fadong Yan ; David J. Metacarpa ; R. Sundaramoorthy ; Dave Fobare ; Pradeep Haldar, 39th IEEE PV Specialists Conference, Tampa FL 10.1109/PVSC.2013.6744879
8. Initial performance of roof top PV arrays of CIGS, CdTe and c-Si in the US northeast climate, J. Nicholas Alexander; R. Sundaramoorthy; David Metacarpa; J.R. Lloyd; Pradeep Haldar, 39th IEEE PV Specialists Conference, Tampa FL 10.1109/PVSC.2013.6745087
9. CIGS PV Reliability - Current practices, Challenges and Approaches, R. Sundaramoorthy, David Metacarpa, J. R. Lloyd, Pradeep Haldar, 40th IEEE PV Specialists Conference, Denver Colorado 10.1109/PVSC.2014.6925327

10. Cost and Market Analysis of Integrative Lightweight PV Systems for Low-Slope Commercial Rooftops, Eric Holton, Ankush Halbe, Adam Garney, Jake Whitbeck, Kevin Sharpe, David Metacarpa, and Pradeep Haldar, 40th IEEE PV Specialists Conference, Denver, CO 10.1109/PVSC.2014.6925495

11. Effects of light-soaking and temperature on different PV technologies, Sandra B. Schujman, Jonathan R. Mann, Christopher Hull, Amara Conteh, Gary Dufresne, Linda M. LaQue Crispin Rice, David Taylor, John Wax, David J. Metacarpa and Pradeep Haldar, 40th IEEE PV Specialists Conference, Denver, CO 10.1109/PVSC.2014.6925468

12. Evaluation of mounting mechanisms for the installation of lightweight PV systems on commercial rooftops, Ankush Halbe, Jennifer Novak, Kevin Sharpe, Graeme Housser, and Pradeep Haldar, 40th IEEE PV Specialists Conference, Denver, CO 10.1109/PVSC.2014.6924873

13. Identification of changes in power through DC granular monitoring, R. Sundaramoorthy, J. Nicholas Alexander, David Metacarpa, J. R. Lloyd, Pradeep Haldar, 40th IEEE PV Specialists Conference, Denver, CO 10.1109/PVSC.2014.6925621

14. Novel Application of Yttria Stabilized Zirconia as a Substrate for Thin Film CIGS Solar Cells, David Fobare, Pradeep Haldar, Harry Efstathiadis, David Metacarpa, John Wax, John Olenick, Kathy Olenick, Viswanathan Venkateswaran, 40th IEEE PV Specialists Conference, Denver, CO 10.1109/PVSC.2014.6924927

15. Structure Evolution In CIGS Deposition: An X-ray Diffraction Analysis With Rietveld Whole Pattern Refinement, Thaddeus A. Reese, Sandra B. Schujman, and Richard J. Matyi, 40th IEEE PV Specialists Conference, Denver, CO 10.1109/PVSC.2014.6925246

16. Application of Derived Optical Models for CIGS to an Optical Monitoring System, Sravan Sunkoju, Sandra B. Schujman, Jonathan R. Mann, John Wax, David J. Metacarpa and Pradeep Haldar, 42nd IEEE PV Specialists Conference, New Orleans, LA 10.1109/PVSC.2015.7355637

17. Correlation of power loss to string and module level performance for arrays of c-Si and CIGS technologies in the North East climate, R. Sundaramoorthy, John Delallo, J. N. Alexander, John Wax, Kevin Sharpe, David Taylor, David Metacarpa, J. R. Lloyd, Pradeep Haldar, 42nd IEEE PV Specialists Conference, New Orleans, LA 10.1109/PVSC.2015.7355700

18. Demonstration of PV Modules with Lightweight Mounting Systems on Commercial Rooftops, Ankush Halbe, Kevin Sharpe, Graeme Housser, David Metacarpa, and Pradeep Haldar, 42nd IEEE PV Specialists Conference, New Orleans, LA 10.1109/PVSC.2015.7355632

19. Reduced Balance of System Costs using Lightweight photovoltaics integrated with roofing material membranes David Metacarpa; Dave Fobare; Adam Garney; Fadong Yan; Daniel Dwyer; Eric Holton; Pradeep Haldar 2015 IEEE 42nd Photovoltaic Specialist Conference (PVSC) 10.1109/PVSC.2015.7355819

20. Lightweight, zero-penetration, pre-formed support molds adapted for rigid thin-film solar modules Graeme Housser; Ankush Halbe; Kevin Sharpe; Pradeep Haldar; Francis Babineau 2015 IEEE 42nd Photovoltaic Specialist Conference (PVSC) 10.1109/PVSC.2015.7355826

21. Evaluation of Protocols for Temperature Coefficient Determination, Sandra B. Schujman, Jonathan R. Mann, Gary Dufresne, Linda M. LaQue, Crispin Rice, John Wax, David J. Metacarpa and Pradeep Haldar, 42nd IEEE PV Specialists Conference, New Orleans, LA 10.1109/PVSC.2015.7355840

22. Application of Derived Optical Models for CIGS to an Optical Monitoring System, Sravan Sunkoju, Sandra B. Schujman, Jonathan R. Mann, John Wax, David J. Metacarpa and Pradeep Haldar, 42nd IEEE PV Specialists Conference, New Orleans, LA 10.1109/PVSC.2015.7355637

23. Experimental Evidence of Multiple Diffusion Mechanisms in Thin-Film Cu(In,Ga)Se_2 N.J. Biderman, S.W. Novak, T. Laursen, R. Sundaramoorthy, P. Haldar, and J.R. Lloyd, IEEE J. Photovoltaics, 5, 1497-1502 (2015). 10.1109/JPHOTOV.2015.2459911

24. Insights into cadmium diffusion mechanisms in two-stage diffusion profiles in solar-grade Cu (In,Ga)Se_2 thin films Appl. Phys. Lett. 107, 232104 (2015); N. J. Biderman, Steven W. Novak, R. Sundaramoorthy, Pradeep Haldar, and J. R. Lloyd 10.1063/1.4937000

25. "Comparison of Performance of PV Modules Subjected to Solar Thermal Humidity Cycles with Modified and Extended IEC Protocols" R. Sundaramoorthy, Jim Lloyd, David Metacarpa, Pradeep Haldar 43rd IEEE PVSC, Portland, OR, Jun 5-10 Jun 2016. 10.1109/PVSC.2016.7749744

26. PV single axis tracker array tests in the Northeast US with CIGS Scott McWilliams; R. Sundaramoorthy; David Metacarpa; Pradeep Haldar 2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC) 10.1109/PVSC.2016.7750282

27. Outdoor performance prediction of photovoltaic modules based on indoor measurements Sandra Schujman; Jonathan Mann; Amara Conteh; Crispin Rice; David Metacarpa; Pradeep Haldar; 2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC) 10.1109/PVSC.2016.7750145

28. Effects of pre-conditioning and testing protocols on performance of different PV technologies Jean M. Brownell; Sandra Schujman; Jonathan Mann; Crispin Rice; Linda LaQue; Gary Dufresne; David Metacarpa; Pradeep Haldar 2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC) 10.1109/PVSC.2016.7749876

29. Life cycle assessment study highlights for New York state based PVMC modeled thin film roll-to-roll CIGS process David Fobare; Shanika Amarakoon; Pradeep Haldar; David

Metacarpal Jennifer Bell; Cyril Vallet 2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC) 10.1109/PVSC.2016.7750016

30. Dissociative diffusion mechanism in vacancy-rich materials according to mass action kinetics N. J. Biderman, R. Sundaramoorthy, Pradeep Haldar, and J. R. Lloyd ; AIP Advances 6, 055211 (2016) 10.1063/1.4950905

Also see publications from the University of Central Florida

Path Forward/Commercialization Plan:

The following is the key excerpts from the potential evaluation of a Tech to Market business plan provided to the DOE for potential future development of the PVMC and its partners. Note that it was determined to review both this pathway and private takeover options as of the submittal of this report.

Start of excerpts of Tech to Market

The U.S. Photovoltaic Manufacturing Consortium (PVMC) is an industry-led consortium which was created with the mission to accelerate the research, development, manufacturing, field testing, commercialization, and deployment of next-generation solar photovoltaic technologies. Formed as part of the U.S. Department of Energy's (DOE) SunShot initiative, and headquartered in New York State, PVMC is managed by the State University of New York Polytechnic Institute (SUNY Poly) at the Colleges of Nanoscale Science and Engineering.

PVMC is a hybrid of industry-led consortium and manufacturing development facility, with capabilities for collaborative and proprietary industry engagement. Through its technology development programs, advanced manufacturing development facilities, system demonstrations, and reliability and testing capabilities, PVMC has demonstrated itself to be a recognized proving ground for innovative solar technologies and system designs.

PVMC comprises multiple locations, with the core manufacturing and deployment support activities conducted at the Solar Energy Development Center (SEDC). The SEDC provides a pilot line for proof-of-concept prototyping, offering critical opportunities to demonstrate emerging concepts in PV manufacturing, such as evaluations of innovative materials, system components, and PV system designs. The facility, located in Halfmoon NY, encompasses 40,000 square feet of dedicated PV development space. The infrastructure and capabilities housed at PVMC includes PV system level testing at the Prototype Demonstration Facility (PDF), manufacturing scale cell & module fabrication at the Manufacturing Development Facility (MDF), cell and module testing, reliability equipment on its PV pilot line, all integrated with a PV performance database and analytical characterizations for PVMC and its partners test and commercial arrays. Additional development and deployment support are also housed at the SEDC, such as cost modeling and cost model based development activities for PV and thin film modules, components, and system level designs for reduced LCOE through lower installation hardware costs, labor reductions, soft costs and reduced operations and maintenance costs.

PVMC Expansion Program

This Technology to Market (T2M) Plan outlines PVMC's strategy to operate independently of its original DOE funding by **building upon its core manufacturing and deployment support competencies (MDF, PDF, data analytics facilities)**, while at the same time

expanding with the industry into the "smart solar" technology space. We define "smart solar" as the incorporation of sensors and smart hardware feeds with secondary data sources to create advanced analytics and algorithms for system improvements and controls. PVMC is confident that the addition of "smart solar" to its portfolio is a natural progression of services, and key to continuing to support the growth of its partner companies as well at the solar industry in the U.S.

This program expansion and the interdependent operation of the PVMC infrastructure and program areas are represented by the new PVMC organizational structure (Figure 1). The left side shows the infrastructure and capabilities which were developed during years 1-5 of the PVMC program. The current infrastructure acts as a tech-to-market pipeline, bringing products from development through commercial scale deployment with associated analysis.

Under the expanded PVMC program, the large scale database and controls facility will be developed, and all areas of the PVMC ecosystem will be linked to provide the highest level of service and benefit to PVMC partners and future service customers.

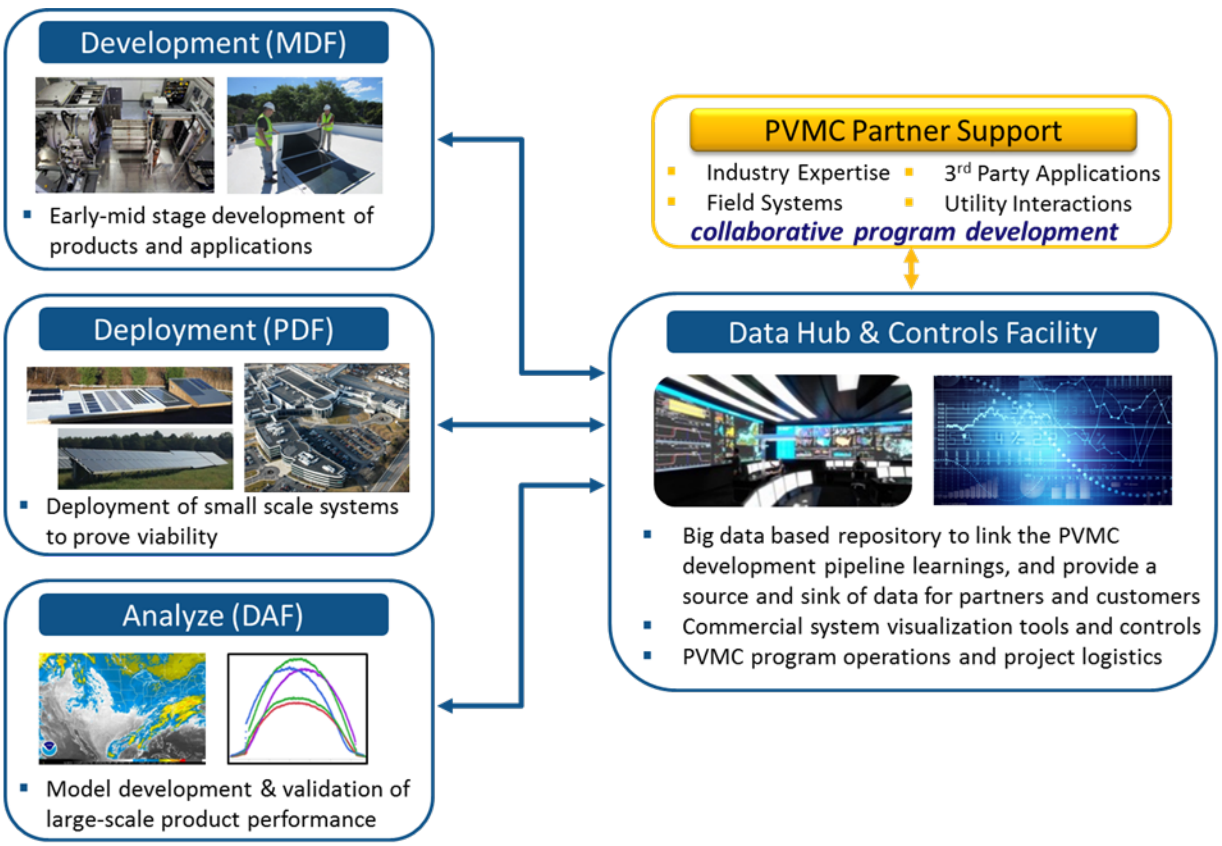


Figure 1: PVMC's Expanded Organizational Structure

As PVMC transitions its clean energy development consortium into a self-sustaining business, its operations will focus on building out its digital infrastructure and providing professional technical, analytical, and advisory services to public and private sector customers in the electric utility, solar, clean energy technology, and energy service arena. PVMC will build on its national presence and years of success, leveraging its experience in the clean energy technology and data marketplace, enabling it to tap into that that marketing which expected to generate over $50 billion in annual revenues by the year 2020. With its existing partner base and an anticipated growth in new public and private sector revenues, PVMC is poised to grow its government and institutional energy business and expand into new markets.

Overall Transition Plan

Vision for Current Program Areas

The link between manufacturing, deployment and the data/sensoring/IoT landscape are becoming increasing apparent. With this in mind, PVMC intends to maintain its focus on its original manufacturing-oriented mission, as well as it new product development efforts, as it continues to expand upon its developments in digital and analytic capabilities. It is the growth and large potential in the data and analytical areas, supported by the manufacturing and deployment infrastructure and competence at PVMC that will let PVMC uniquely stand out in this technology space. Looking forward, PVMC's expansion in to the distributed energy resource database and analytical / communication capabilities will be an increased focus in its growth plan.

The PVMC vision for the manufacturing programs relies on the feedback loop enabled by the ever expanding access to field data. This feedback loop allows for product improvements/defect mitigations to be developed much faster, or alternatively enables increased sales due to product outperformance recognized early in the deployment process. Both of these are of great value to PVMC partner companies.

- **Manufacturing and Product Development**

PVMC's product development group will continue to assist entrepreneurs and existing companies with the development of innovative products, systems, and technologies using the infrastructure and knowledgebase developed during its initial years of growth. These "new product introduction" services cover the end-to-end spectrum of the product development life cycle, including early stage concept testing, prototyping, engineering and design, comprehensive product testing, manufacturing, scale-up services, and cost modeling.

The MDF infrastructure is the foundation for this development work. Efforts will continue where and when needed, with a focus on responding to data-driven performance and reliability issues due to manufacturing variations and/or deficiencies. This includes data derived from new products being developed and tested at the PVMC PDF.

- **Product Deployment**

Systems installed and tested at the PDF, which generally are in the near-to-deployment phase, rely on the PDF services to validate product claims and identify weaknesses. Through these services, PVMC has enabled its partners to reduce hardware costs, optimize complex systems, and improve operational efficiency and manufacturability.

PVMC's development strategy is based on proven methods and experiences in program management and solar commercialization. Although PVMC is capable of covering the entire product market, we are investigating the following areas as tier-one targets. These include the products and services in legacy areas where PVMC has seen continued industry involvement and support, as well as new areas of development into sensoring platforms and integration of technologies to enable PV expansion:

- Cell and Module Manufacturing & Scale-Up
    - Assisting the expansion of the U.S.-based solar manufacturing industry (including cells, modules, BOS components, ancillary hardware)
- Solar Rooftop Hardware & Systems
    - The design, manufacturing and testing of new PV mounting/racking systems
- Optimizing Systems Integration
    - Packaged solar-battery systems (systems integration)
    - Solar + smart inverters
    - Solar + Energy Efficiency and other distributed energy resources (DERs)
- Digitally-enabled PV systems, products, and platforms
    - Improving existing solar products and creating more value by applying advanced analytics and/or digital capabilities (e.g., advanced sensors and communications)
    - Creating new platforms and applications for the solar market

Expansion of Services – Big Data Integration and Systems Controls

PVMC will organize its expansion around its existing tech-to-market pipeline infrastructure. These expanded services will include a new "big data" based analytics infrastructure, and a central O&M and controls facility which benefits from each of the PVMC sub-units, acting as a proving ground for system operations and maintenance, and utility interaction products and services. In addition the analytics infrastructure will include energy efficiency efforts targeted at the commercial and industrial space that is expected to increase PV deployment through lessening the stress on the grid through a lower demand needs in targeted areas.

- **Big Data System: PVMC Database for Operations and Maintenance of Energy (DOME)**

The PVMC System Performance and Operations (SPO) group has developed a SQL and JMP based data storage and analysis system. This platform has proven successful in supporting SPO specific predictive performance and O&M projects, as well as the testing and development services offered at the MDF and PDF. While valuable, this system is limited in its capacity and interoperability.

"Big data" and "big data analytics" are concepts which have grown out of the exponential increases in data and data sources in recent years. These systems allow for massive amounts of information to be collected, sorted, and analyzed as needed. The solar market is evolving in the direction of these big data systems. An increasing variety of sources are providing meaningful data which could be exploited for product development, integration opportunities, reliability feedback, etc. These include but are not limited to direct hardware components such as smart inverters, micro-inverters, dc optimizers, weather sensors, grid power quality sensors, and smart meters as well as indirect feeds such as satellite imaging and maintenance reports. Combining these and other data feeds into a single system has the potential to revolutionize the PV industry.

PVMC's new data storage and analytics system, PVMC Database for Operations and Maintenance of Energy (DOME), will be structured in the "data lake (DL)" format to allow for infinite scale up and multiple additional data sources to be added without requiring a significant amount of pre-structuring. This is important, as PVMC sees this system as an all-encompassing data repository, first incorporating inverter level data, and then expanding as the industry requires providing the needed inputs for data analysis and algorithm development work.

Big data analytics toolsets (Spark, Samoa, Splunk, Cloudview) will be used by PVMC & partners to develop analytics tools and system controls algorithms based on historical and real-time data fed into the data lake. The controls feedback loop will also benefit from the machine learning process enabled by the big data architecture. For example, in the case of developing inverter self-control functions, as more inverter data is input into the system under different conditions, and the line sensor feeds measure the resulting influence on the grid, the system will continuously improve its prediction algorithm for conditioning and curtailment, or diversion to energy storage solutions.

- **Distributed Energy Controls: PVMC Control Facility (CF)**

The massive increases in PV systems and other DERs are changing the makeup of the energy distribution systems. In areas with high PV penetration, the grid must be able to respond to a number of systems changes. These include variables such as the natural solar cycle & resulting ramp up and ramp down, intermittent generation due to weather, and mid-day production peaks. These variables require a different controls scheme than typical base load stations or peak load backups.

At times of overproduction relative to the load, the grid operator must have the ability to curtail or divert to storage the PV system as needed to protect the grid infrastructure. Ideally, this would occur at the PV system level through smart inverter controls.

At times of underperformance, the response is limited to pulling power from storage resources or redistributing the power from other grid resources. Both of these responses benefit from some level of predictive analysis enabling the systems to respond as the interruption occurs.

In both of these cases, a system is needed which can facilitate controls and predictive analysis either directly to PV sites through a central system or indirectly by feeding algorithms to remote controls units. While a number of very large organizations have the internal ability and financials to meet these challenges, the majority of the DER operations and asset management organizations are unable to overcome these barriers to enter into this expanded marketplace without this capability. This is the intent for the PVMC Controls Facility (CF). The CF and DOME are natural partners in creating a data-based prediction and response system.

Execution Strategy

PVMC will ramp-up its DOME and CF capabilities in phases over a three year period, beginning with an initial infrastructure build out and program integration, progressing to an expansion of DOME and CF services, and completing as a fully operational capability for use by partners, outside developers, financiers, regulators, and other interested parties.

Summary and Commentary

A truly collaborative consortium model, especially one focused on manufacturing, works best when the national or global market capitalization is potentially very large or for a burgeoning industry with common challenges. PVMC intended to address this with both a c-Si focus (headed by UCF, with the knowledge that > 90% of the global solar market is c-Si based), and thin film CIGS focus as a potential market disruptor that needed alignment and industrial coordination. For programs focused on thin film manufacturing and the reality of the market size and disproportional representation by start-up companies, critical mass for collaboration was limited. This critical mass should encourage member companies to have "assignees" doing much of the consortium activities. CIGS thin manufacturers tend to have unique manufacturing methods and are reluctant to accept industry standards and protocols, therefore a focus on the deployment side was deemed more effective and allowed for large developers to help drive product and integration designs. The principal reasons for joining a consortium are (1) to achieve economies of scale, (2) to share innovation risks, (3) to set standards for a new technology, (4) and to share complementary knowledge. In year one and two, PVMC conducted a comprehensive CIGS roadmap, forming groups comprised of diverse industry stakeholders. It was apparent that the industry has been highly fragmented on approaches to manufacturing and market focus, without any dominant OEM suppliers. The consortium flexibility was key in supporting industry activities and addressing quickly changing market dynamics. This flexibility was highlighted when PVMC went through the "pivot" to focus more down-stream, where PV developers, data analytic companies, module and BOS manufacturers worked collaboratively to reduce cost, improve performance, designing for O & M, and to explore new product innovations. C & I developers, array owners, and O & M entities have considerable interest in a NERC certified data center with full capabilities to monitor and analyze PV array performance because such data centers are prohibitively expensive for most C & I stakeholders to establish or to participate in.

A consortium in a "high-risk, high-reward" technology development area can drive innovations and an industry market segment, although careful considerations need to be taken when companies participate in an area where the market changes faster than consortium approvals may allow for high value impact.

Acronym Definitions:

AFM	Atomic Force Microscopy
Ag	Silver
AHP	Analytic Hierarchy Process
ALT	Accelerated Lifetime Tests
ANSI	American National Standard Institute
APC	Advance Process Control
ASCE	American Society of Civil Engineers
BEOL	Back End Of the Line
BKMs	Best Known Methods
BOM	Bill Of Materials
BOS	Balance of System
BOS-CAT	Balance OF Systems -Cost analysis tool
BP	Budget Period
C	Centigrade
C&I	Commercial and Industrial
CIPV	Commercial & Industrial Photovoltaics
CAPEX	Capital Expenditure
Cd	Cadmium
Cd-Te	Cadmium-Tellurium (Cd-Telluride)
CF	Control Facility
CIGS	Copper Indium Gallium Selenium (Copper Indium Gallium di-Selenide)
CME	Coefficient of moisture contraction
CNSE	College of Nanoscale Science and Engineering
CTE	Coefficient of thermal expansion
c-Si	Crystalline-Silicon
C-V	Capacitance-Voltage
CZ	Czochralski
DER	Distributed Energy Resources

DOE	Department of Energy
DOME	Database for Operations and Maintenance of Energy
EL	Electroluminescence
EPC	Engineering, Procurement, and Construction
EPRI	Electric Power Research Institute
ESH	Environment Health and Safety
ETAB	Executive Technical Advisory Board
FF	Fill Factor
FOM	Figure Of Merit
FSEC	Florida Solar Energy Center
FT	Flash Tester
FTIR	Fourier Transform Infrared Spectroscopy
GDP	Gross Domestic Product
GSE	Global Solar Energy
h	hours
HR-TEM	High Resolution-Transmission Electron Microscope
HVM	High Volume Manufacturing
IALT	Indoor Accelerated Lifetime Tests
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet Of Things
IPV	Integrated Photovoltaic
IR	Infrared-Imaging
Isc	Short Circuit Current
I-V	Current-Voltage
Jsc	Current Density
kW	Kilo Watt
LBIC	Laser Beam Induced Current
LCOE	Levelized Cost of Energy
LPV	Lightweight PV

MDF	Manufacturing Development Facility
MEA	Marketing and Economic Analysis
MES	Manufacturing Execution System
MW	Megawatt
Na	Sodium
NERC	Non Residential Energy Code
NP	NewPort
NPI	New Product Introduction
NPI-CIPV	New Product Introduction for Commercial & Industrial Photovoltaics
NREL	National Renewable Energy Laboratory
NY	New York
O	Oxygen
O&M	Operations & Maintenance
OEM	Original Equipment Manufacturer
OH	Hydroxide
OMT	Optical Monitoring Terminal
OR	Oregon
Out	Outdoor
PAN	Panorama Database file
PC	Photoconductance
PDF	Prototype Demonstration Facility
PERC	Passivated Emmiter Rear Cell
PL	Photoluminescence
PV	Photovoltaic
PV-GRID	Photovoltaics for Grid Regulated Interconnection and Deployment
PVMI	Photovoltaic Manufacturing Initiative
PVSC	Photovoltaic Specialist Conference
PUC	Public Utility Commission
QC	Quality Control

R&D	Research and Development
R2R	Roll to Roll
RESC	Roadmap Executive Steering Committee
RH	Relative Humidity
RMI	Rocky Mountain Institute
RMS	Root Mean Square
RTC	Regional Test Centers
SAM	Scanning acoustic microscope
SEDC	Solar Energy Development Center
SEMATECH	Semiconductor Manufacturing Technology
SEMI PV	Semiconductor Manufacturing Initiative for Photovoltaics
SOPO	Statement of Project Objectives
SPC	Statistical Process Control
SPO	System Performance and Operation
SPO_ROI	System Performance and Operation for Return on Investment
SQL	Structured Query Language
STC	Standard Test Conditions
SUNY Poly	State University of New York Polytechnic Institute
SOW	Statement Of Work
T2M	Technology to Market
TCO	Transparent Conducting Oxide
TIA	Technology Investment Agreement
TPO	Thermoplastic Polyolefin
TW	Terra Watt
TWG	Technical Working Group
UCF	University of Central Florida
UL	Underwriter Laboratories
US-PVMC	U.S. Photovoltaic Manufacturing Consortium
VC	Venture Capital
Voc	Open Circuit Voltage

VT	Vermont
wf	Wafers
WG	Working Group
Wp	Watt Peak
XRF	X-Ray Fluorescence
XRF	X-Ray Fluorescence
ZnS	Zinc Sulphide